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CRYSTAL RECTIFIERS FOR ELECTRIC CURRENTS AND ELECTRIC OSCILLATIONS.

PART II. CARBORUNDUM, MOLYBDENITE, ANATASE, BROOKITE.

BY GEORGE W. PIERCE.

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INTRODUCTION.

Concerning Part I. — Carborundum had been found by General Dunwoody[1] to be capable of acting as a receiver for the electric waves of wireless telegraphy. Having learned of this property of carborundum, the writer thought that a further study of the electrical behavior of this substance would be interesting. In the course of this study, an account of which has been published in the PHYSICAL REVIEW[2] for July, 1907, it was discovered that when a piece of carborundum is placed in a clamp between contact electrodes, the hetereogeneous conductor consisting of the carborundum and the electrodes permits the passage of a greater current in one direction than in the reverse direction under the same applied voltage. The device can be used as a rectifier for small alternating currents and oscillations. The phenomenon is very striking. For example, with one specimen under an electromotive force of 30 volts the current in one direction is 4,000 times as great as the current in the opposite direction under the same external voltage.

Although the rectified current is not large (in the case just cited, 3 milliamperes in one direction and .00075 milliampere in the opposite direction) such a rectifier, being constructed entirely of solid parts, possesses sufficient permanence and constancy to permit of many useful applications, where the detection and measurement of small alternating currents is required. As an example of such applications details are given in Part I. of the employment of the rectifier in the construction of an alternating current voltmeter operable with an extremely small consumption of energy.[3]

Questions Arising in Connection with the Phenomenon. — Many questions of theoretical interest arise in connection with the phenomenon. Is the action localized at the surface of contact between the crystal and the metallic electrode? Is the action due to electrolytic polarization? Is the action thermoelectric, conditioned on unequal heating of the two electrode contacts? If the phenomenon is novel, how is it related to the hitherto studied properties of conductors?

In the experiments on carborundum performed by the writer the

[1] Dunwoody, U. S. Patent, No. 837,616, issued December 4, 1906.
[2] Pierce, PHYS. REV., Vol. 25, pp. 31–60, 1907.
[3] G. W. Pierce, U. S. Patent, No 879,061.

investigation of these questions met with limitations on account of the occurrence of the carborundum in discrete masses to which electrodes could not be rigidly attached; so that the conditions at the electrodes could not be widely varied. However, by increasing the pressure of the electrodes against the carborundum beyond a certain limit, and by cathodically platinizing the surfaces of the carborundum at both the contact areas, the rectification though not entirely eliminated was rendered very imperfect; that is to say, the ratio of the strength of the current in one direction to that in the reverse direction approached unity. On the other hand, platinizing one only of the surfaces of contact, while the other surface was left unplatinized, generally rendered the rectification more nearly perfect. This fact indicated that the seat of the action was the area of contact with the electrodes, and that the action at the two contacts were in opposition to each other, so that when the action at one of the contacts was reduced by platinizing, the rectification at the other contact appeared more pronounced.

These characteristics of the phenomenon are consistent with the view that *the rectification is conditioned on the localization of the energy of the circuit at the high resistance boundary between the two different classes of conductors, the crystal and the metallic electrode.*

Now such a localization of energy at the boundary of the two conductors is favorable to the production of electrolytic polarization, if we may have electrolytic polarization in solids, and is also favorable to the production of a thermoelectromotive force, either of which might result in rectification.

Nevertheless, in Part I., a number of experiments are described which were taken to indicate that neither electrolysis nor thermoelectricity plays an important part in the phenomenon.

On the Question of Electrolysis, the following experiment, performed since the publication of Part I., has a bearing.

Experiment Showing Permanence of the Carborundum Rectifier. — In confirmation of the absence of electrolytic polarization, a durability test of the rectifier has later been made as follows: A crystal of carborundum enclosed in a glass tube with a few drops of oil[1] and held between brass electrodes, one of which was under

[1] The oil was put in to prevent accumulation of moisture.

tension of a spiral spring, was kept under almost daily observation [1] from October 23, 1907, until March 18, 1908. During this time more than 1,200 measurements were made of the direct current obtained through the crystal under different direct and alternating voltages. The rectifier was kept in a thermostat and subjected to various long periods of heating and cooling ranging from 0° to 80° C. Notwithstanding the long continued exposure of the crystal to large changes of temperature, and notwithstanding the frequent loading and occasional overloading of the rectifier with current, it was found at the end of the series that the values of the direct current obtained from the crystal under a given applied alternating voltage over a range of current from 4 to 400 microamperes (direct) and a range of voltage between 1.5 and 6 volts (alternating) did not differ from the corresponding values at the beginning of the series by an amount exceeding the limit of accuracy of the experiment, which was about one third of 1 per cent.

This experiment shows that if there is any kind of electrolytic action, it must be of such a character as not to change the nature of the electrodes or of the crystal.

On the Question of a Possible Thermoelectric Origin of the Phenomenon. — It is apparent that the disposition of the carborundum for the best rectification is exactly the most favorable disposition for the development of a thermoelectric voltage at the high resistance contact. This voltage, being always in one direction, by superposition on an alternating current through the crystal, might give rise to a unilateral cycle through the crystal. In Part I., several experiments are described which present evidence adverse to this explanation, and the opinion is expressed that "heat is practically a negligible factor in the process."

However, since it is very important to exclude the possibility of bringing the experiments into consistent relation with thermoelectricity before admitting that we are dealing with a new phenomenon, the question of the applicability of the thermoelectric explanation is taken up anew in the present account.

[1] This series of measurements were carried out by Mr. K. S. Johnson, to whom the writer wishes to express his sincere thanks. The experiment was finally discontinued on account of the accidental melting of the cement holding in the ends of the tube.

Extension of the Experiments to Other Crystals. — Prior to the publication of Part I., the writer had found a number of other crystals showing the rectifying property similar to carborundum. These have now been under investigation for a period of more than a year, and though the work is by no means completed, it is thought that an account of the experiments as far as they have gone may be of interest. The present account deals with the rectifying action of anatase, brookite and molybdenite in contact with a metallic electrode.

Anatase and Brookite.

Anatase. — Anatase, an octahedral crystal of oxide of titanium with the chemical formula TiO_2, was found to rectify quite markedly when placed in a clamp, under a contact pressure of 1 to 3 kilograms. Current-voltage curves [1] of anatase, with a diagram of the disposition of the crystal in the experiment, are given in Fig. 1. The

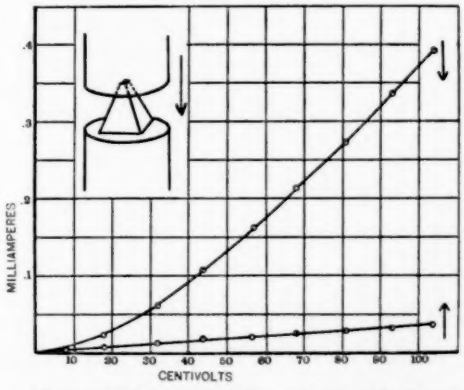


Fig. 1. — Current-voltage curves for anatase, with direct current.

upper curve was obtained when the current was through the crystal in one direction, the lower curve was with the current in the opposite direction, as indicated by the arrows. The contact pressure in this experiment was 2 kilograms. These curves have the same general form as those obtained in the experiments on carborundum. By a

[1] The current-voltage curves were drawn in Part I. with positive coördinates when the current was in one direction and negative coördinates when the current was in the opposite direction. In order to economize space in the present account, both the positive and negative currents are drawn in the same coördinate quadrant. This has the advantage of permitting an easier comparison.

comparison with Part I., it is seen, however, that the anatase gives much larger currents with a small applied voltage than does the carborundum. This characterizes the anatase as a much more sensitive rectifier for small alternating voltages and as a much more sensitive detector for electric waves than is the carborundum.

Brookite. — This is another crystal form of TiO_2, which was found to serve as a rectifier of small alternating currents with about the same sensitiveness as anatase. Although a considerable amount of time was spent in experimenting with anatase and brookite, these substances, occurring, like carborundum, in discrete pieces to which terminals could not be attached, did not serve to throw much light on the phenomenon. Numerical data in regard to them are, therefore, omitted.

MOLYBDENITE.

One of the most sensitive and interesting of the rectifiers thus far investigated makes use of molybdenite as a member.[1] Molybdenite, with the chemical formula MoS_2, is a mineral occurring in nature in the form of tabular hexagonal prisms with eminent cleavage parallel to the base of the prism. The cleavage of the crystal resembles that of mica, and thin sheets of the mineral several square centimeters in area may be scaled off from a large crystal of molybdenite. These sheets have a metallic lustre and look not unlike sheets of lead foil. They can be readily electroplated with copper, so that connecting wires may be soldered to them. This property, together with the thinness of the sheets and the ease with which the thermoelectric property of the substance may be studied, admirably adapts it to the present experiments.

The Molybdenite Rectifier. — The rectifying action of the molybdenite was first obtained with a thin, flat specimen of the mineral held between flat contact electrodes in a clamp of which the two jaws were insulated from one another. With this form of mounting the molybdenite also acts as a receiver for electric waves with or without a battery in the local circuit.

It was soon found, however, that the apparatus was more sensitive

[1] See also G. W. Pierce, "A Simple Method of Measuring the Intensity of Sound," Proc. Am. Acad., Vol. 43, p. 377, February, 1908, in which the molybdenite rectifier was employed.

as a receiver for electric waves and as a rectifier, when one of the contacts between the molybdenite and the electrode had a high resistance. A form of mounting in which this is attained is shown in section in Fig. 2. T is a threaded brass post on the top of which is placed a disc of mica N. On top of the mica is a thin circular disc of the molybdenite M with an area of about 1 square centimeter, leaving a projection of the mica beyond the periphery of the molybdenite. A hollow cap D, threaded inside and having a conical hole at the top, is screwed down on the post T so as to clamp the molybdenite between the mica disc [1] and the annular shoulder of the cap, with the upper surface of the molybdenite exposed above. At the free surface of the molybdenite contact is made with metallic rod P.[2]

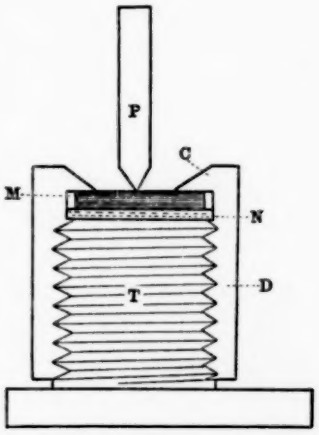


Fig. 2. Holder for molybdenite.

The rod P was either supported unadjustibly as in the author's experiments on sound,[3] or it was mounted in a manner to permit of ready adjustment as is shown in Fig. 3. The clamp K containing the molybdenite is metallically connected with the binding post H (Fig. 3). Another binding post is attached to the metallic block A, on top of which is supported a stout spring B. Through a hole in B provided with a set screw, the rod P is allowed to drop down into contact with K. The set screw is then tightened against P, and the final adjustment is made by the slow-motion screw S. The apparatus is connected in circuit by means of the binding posts, so

[1] The purpose of the mica disc under the molybdenite is to confine the current as much as possible to the upper layer of the molybdenite. This was done so as not to complicate the phenomenon by conduction across the laminæ of the substance, and also so that when the detector is immersed in oil in some of the later experiments, the oil shall have free play over the conducting surface and over the contacts, and serve the better to avoid possible changes of temperature of the essential parts of the apparatus.

[2] In the diagrams of Fig. 2 and Fig. 3, the lower end of the rod P is shown pointed. It is found, however, that the end of the rod P may be blunt or even flat with an area as great as 4 sq. mm. without much loss of sensitiveness of the instrument as a receiver for electric waves or as a rectifier.

[3] Loc. cit.

that the current of the circuit is made to enter the molybdenite through the contact area between P and the molybdenite and to leave by way of the contact between the molybdenite and the cap C, or the reverse. It is found that a larger current flows in one direction

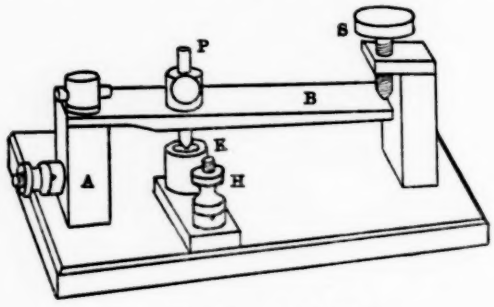


Fig. 3. Mounting of molybden te.

than in the reverse direction for a given applied elecromotive force.

Current-voltage Characteristic of the Molybdenite Rectifier. — A large number of current-voltage curves of the molybdenite rectifier with the form of mounting shown in Fig. 3, have been taken both with direct and alternating applied voltages. Two sets of these curves, with the corresponding tables are here given. In taking the observations of Fig. 4, Table I., the rectifier was submerged in a constant temperature oil-bath. The oil was rapidly stirred and had free access to the surface of the molybdenite and to the point contact between the molybdenite and the copper rod. A steady voltage was applied to the terminals of the rectifier, and the current through the crystal was measured. The voltage was then reversed and the current again measured. The process was repeated with various values of the voltage. These values thus obtained in the oil-bath were found to be the same as the corresponding values when the rectifier was in air at the same temperature. That is, the presence of the oil about the rectifying contact did not materially affect the process.

The values of Table I. are plotted in the curves A and B of Fig. 4. A is the curve obtained when the current was sent from the copper to the molybdenite, B the corresponding curve when the current was sent from the molybdenite to the copper. These curves

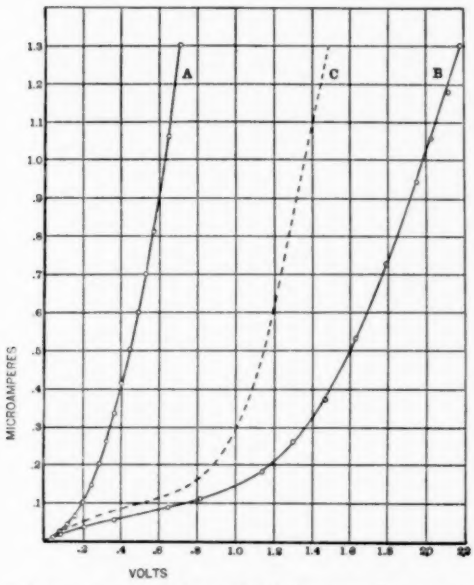


Fig. 4. Current-voltage curves of the molybdenite rectifier. *A*, current from copper to molybdenite; *B*, current from molybdenite to copper; *C*, excess voltage.

TABLE I.

Current-Voltage Values for the Molybdenite Rectifier.

Current from Copper to Molybdenite.		Current from Molybdenite to Copper.	
Volts.	Microamperes.	Volts.	Microamperes.
.0407	.012	.082	.020
.0815	.025	.203	.038
.122	.043	.363	.058
.163	.068	.651	.090
.203	.102	.815	.114
.244	.147	1.140	.185
.285	.202	1.300	.261
.326	.262	1.465	.375
.363	.337	1.630	.534
.407	.415	1.79	.732
.447	.504	1.96	.947
.488	.600	2.03	1.056
.529	.700	2.12	1.180
.570	.812	2.18	1.306
.651	1.062		
.710	1.306		

resemble those obtained in Part I with carborundum. The molybdenite rectifier is, however, seen to operate with a much smaller resistance than the carborundum rectifier. This makes the molybdenite rectifier applicable to use with smaller voltages than the carborundum, consequently the molybdenite rectifier is a more sensitive detector for electric waves or for small alternating voltages than the carborundum rectifier. In fact, the molybdenite rectifier, with selected specimens of molybdenite, when used as a detector for electric waves, is, so far as the writer can judge, equal in sensitiveness with the most sensitive detectors heretofore employed in wireless telegraphy. Also the molybdenite rectifier, giving comparative large values of direct current for small values of applied alternating voltage, affords a sensitive method of measuring the small alternating voltages arising in telephony and in experiments on sound. Application of the rectifier to the measurement of sound has been made in a paper entitled a "Simple Method of Measuring the Intensity of Sound."[1]

Referring again to Fig. 4, attention is called to the dotted curve *C*. This curve is calculated from the curves *A* and *B* by subtraction of corresponding abscissas. The curve *C*, therefore, represents the excess of voltage required to force the current from the molybdenite to the copper above that required to send an equal current in the opposite direction. The table of values for curve *C* follows as Table II.

TABLE II.

Excess of Voltage to Send Current from MoS_2 to Cu above that to Send Current from Cu to MoS_2.

Microamperes.	Excess Volts.	Microamperes.	Excess Volts.
.05	.18	.70	1.24
.10	.515	.80	1.27
.20	.89	.90	1.32
.30	1.01	1.00	1.36
.40	1.09	1.10	1.40
.50	1.15	1.20	1.45
.60	1.19	1.30	1.48

The current-voltage values for the molybdenite rectifier differ for different specimens and for different adjustments of the same speci-

[1] Pierce, Proc. Am. Acad., Vol. 43, p. 377, February, 1908.

men. The results of another experiment, in which larger values of the current and voltage are employed, are given in Table III. These values were obtained with a specimen mounted somewhat differently from the mounting in Fig. 3, in that, in order to eliminate any possible uncertainty from the use of the clamp holder *K* (Fig. 3), the tight-contact terminal was soldered to a copper plated area on the molybdenite, and the sheet of molybdenite with its soldered terminal were held down upon a block of wood by means of a mica covering screwed to the block. A hole through the mica covering admitted the contact rod *P*.

TABLE III.

Current-Voltage Values for the Molybdenite Rectifier. Larger Currents.

Current from Copper to Molybdenite.		Current from Molybdenite to Copper.	
Volts.	Milliamperes.	Volts.	Milliamperes.
.5	.20	2.0	.02
.6	.50	4.5	.10
.77	1.00	5.27	.25
.84	1.50	7.1	.55
.92	2.00	8.6	1.15
1.07	2.50	10.1	2.20
1.15	3.00		
1.32	4.00		
1.52	5.00		
1.70	6.00		
1.88	7.00		
2.00	8.00		
2.15	9.00		
2.22	10.00		

The values recorded in Table III. are plotted in Fig. 5. By a reference to the curves or to the table it is seen that the rectification at 10 milliamperes is practically perfect; the current from the molybdenite at 2.2 volts is 10 milliamperes, while the current in the opposite direction at the same voltage is about .02 milliampere. This is a larger value of the rectified current, at practically perfect rectification, than I was able to obtain with the carborundum rectifier. It was, therefore, decided to recur to the attempt to obtain an oscillographic record of the phenomenon, as had been attempted

with only partial success in the study of carborundum. The result in the present experiment is highly satisfactory.

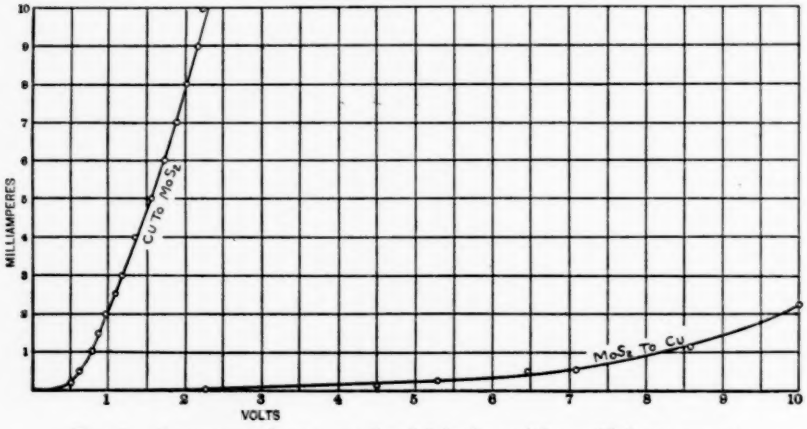


Fig. 5. Current-vocnltage rves of molybdenite recitfier, with large current.

OSCILLOGRAPHIC RECORDS OF RECTIFIED CYCLE.

Method of Obtaining the Oscillograms. — After a prolonged attempt to use an Einthoven galvanometer, which was found to be impracticable on account of the natural period of the "string" of the galvanometer, the Braun's tube oscillograph was employed A sketch of the oscillographic apparatus is given in Fig. 6. The

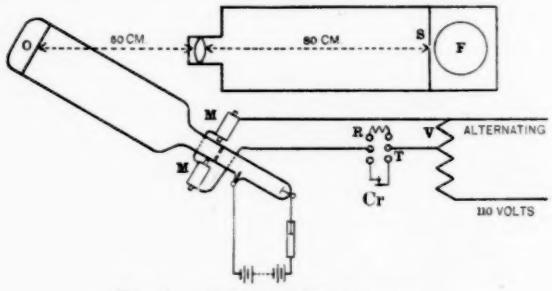


Fig. 6. Oscillographic apparatus.

Braun's tube was filled with hydrogen and was pumped to the vacuum at which it has its highest sensitiveness.[1] The high-potential current through the tube was supplied by Professor Trowbridge's

[1] My thanks are due to Mr. E. L. Chaffee for very carefully pumping out the tube for me, and for other valuable assistance with the oscillographs.

40,000-volt storage battery, which he kindly placed at my disposal. Usually only 20,000 volts of the battery were employed, and this was controlled by means of a running-water rheostat in series with the battery and the tube.

The cathode beam in the tube produced a luminescent spot on the fluorescent screen at *O*. The electromagnets, through which the current to be oscillographed was sent, were placed above and below the Braun's tube at *MM*. Therefore, the deflection of the spot was in a horizontal line perpendicular to the plane of the figure. The photograph of the moving luminescent spot was taken on a sheet of bromide paper carried by a rotating drum *F*, which made 20 revolutions per second about a horizontal axis. This drum was enclosed in a light-tight box at the back of an improvised camera. A horizontal slit *S*, immediately in front of the rotating drum, shut off all luminescence in the tube except that in the line of motion of the spot.

The rotating drum was driven by a synchronous motor operating on the 60-cycle alternating current mains of the laboratory. The alternating current sent through the rectifier and the deflecting magnets was taken from the same supply. The synchronism of the drum with the deflections of the luminescent spot was so perfect that exposures of four minutes could be made, during which time the image of the spot moved over the sensitive paper 4,800 times, without any failure of perfect superposition, and without any appreciable fogging of the paper.

The deflecting electromagnets *MM* had a combined resistance of 436 ohms, and were provided with soft iron cores about 6 millimeters in diameter. With these deflecting coils a direct current of 1.5 milliamperes gave a deflection of 1 cm. on a ground glass put in the place of the sensitive paper at the back of the camera. A calibration for different values of direct current through the coils showed the deflections of the light spot to be proportional to the current, and for the small values of current employed showed no evidence of hysteresis in the iron.

The Oscillographic Records. — Reproductions (reduced to $\frac{1}{3}$) of a characteristic set of the oscillographic records obtained are given in Plate I. Oscillograph No. 1 was taken with the molybdenite rectifier adjusted to give practically perfect rectification. No. 2 is with the

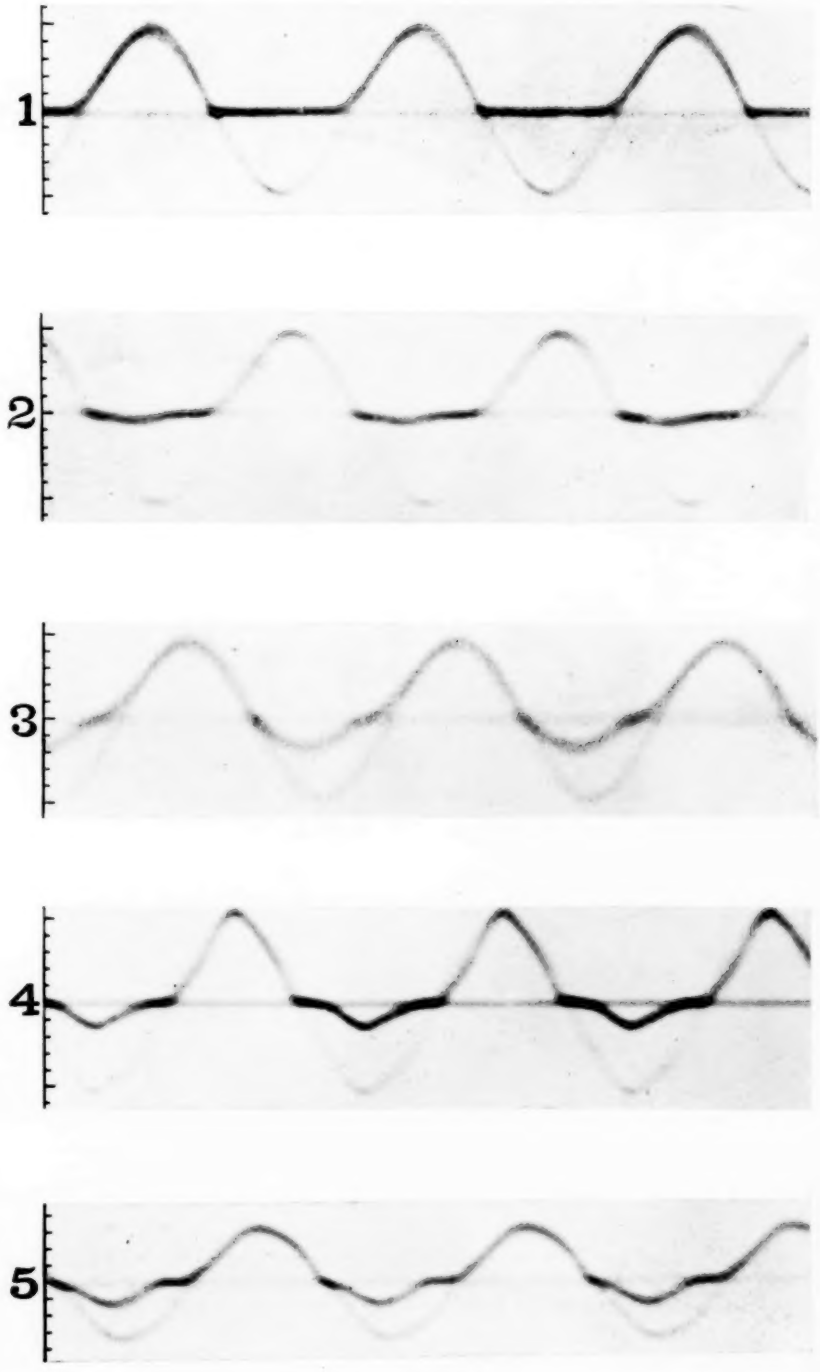
same rectifier slightly out of adjustment (overloaded), so that the rectification is less perfect. No. 3 is with the same rectifier further out of adjustment. No. 4 is an oscillographic record with the carborundum rectifier. No. 5 is with the rectifier of brookite. In taking No. 2, the rectifier was submerged in oil, to test the effect of cooling, which was found to have no effect.

In making these records the following steps were taken: The drum carrying the film was set rotating. The high-potential current was started in the tube. The potential V (Fig. 6) and the contact of the rectifier were adjusted so that the deflection of the luminescent spot on the fluorescent screen was wholly or chiefly to one side of the zero position. Exposure of about 2 minutes was then made. This exposure gave the heavy line of the oscillograms. The switch at T was then thrown open, so that the luminescent spot came to its zero position. The exposure in this position was made for a shorter time of about 40 seconds. This traced the light straight line along the center of the picture, and gave the axis of zero current. The switch T was then thrown to the position to put the resistance R in the circuit in place of the crystal. The resistance R had been previously adjusted so that the amplitude of the deflection with R in the circuit should coincide with the amplitude with the crystal in the circuit. With the resistance R in circuit an exposure of about one minute was made, giving the light sinusoida-curve of the picture.

On each picture the three exposures give, therefore, (1) the form of the rectified cycle as a heavy line, (2) the position of the axis of zero current, as a straight line through the figure, and (3) the form and position of the alternating-current cycle when an equivalent resistance R is substituted for the rectifier. The last-named cycle appears in the pictures as a thin-lined sine curve. This curve is in phase with the impressed voltage immediately about the crystal, and is referred to below as the "voltage-phase curve."

In tracing all the curves, the motion of the light spot over the paper is from left to right; the time coördinate is, therefore, the abscissa of the curves and is drawn as usual from left to right.

The scale drawn in ink at the left-hand margin of each picture gives the value of the current; one division being one milliampere.



G. W. PIERCE
Crystal Rectifiers

A tabular description of the conditions under which each of the records was taken is contained in Table IV.

TABLE IV.

Tabular Description of the Oscillographic Records of Plate I.

No.	Material of Rectifier.	Condition.	Maximum Rectified Current in Milli-amperes.	R.M.S. Alternating Volts.	Equivalent Resistance in Ohms.
1	Molybdenite.	Good adjustment.	4.9	3.54	400
2	"	Out of best adjustment. Submerged in oil and overloaded.	4.9	3.54	400
3	"	Out of best adjustment. Overloaded.	4.5		
4	Carborundum, platinized on one side.	Overloaded.	5.4	22.0	6000
5	Brookite	"	3.0	2.22	992

A discussion of the records follows.

Oscillograms 1, 2 and 3, Molybdenite. — The pressure of the copper rod[1] against the molybdenite for good rectification is slight, and is somewhat difficult to attain. Some points of the crystal are more sensitive than others, and the crystal has to be moved around under the copper contact and tried at several different points before the best adjustment can be found. Oscillogram No. 1, Plate I., was taken with a molybdenite rectifier in good adjustment. The rectification in this case is seen to be practically perfect; the cycle through the specimen consists of a nearly sinusoidal curve for one half-period and a practically straight line for the other half-period. The large current flows from the copper to the molybdenite, and the zero current from the molybdenite to the copper.

When the pressure on the contact was increased until a smal negative current was permitted to pass, oscillogram No. 2 was obtained. Increasing the pressure still more so as to get a larger negative current gave oscillogram No. 3.

One object in taking these oscillograms, together with the voltage-phase cycle, was to see if there is any evidence of lag of the rectified cycle with respect to the voltage-phase cycle. *No such*

[1] The end of the copper rod in contact with the molybdenite had an area of 4 sq. mm.

lag appears. On the other hand, the rectified cycles *lead* their respective voltage-phase cycles at three positions:

The first of these positions of lead is at the part of the cycle in which the rectified current approaches the zero axis after having traversed the upper half of the curve. This advance, which is so small as to be just perceptible in the oscillograms, amounts to about 1/6000 of a second.

A second, somewhat larger, lead of the rectified cycle ahead of the voltage-phase cycle is at the point of rising from the axis after the rectified current has followed for a half period along the zero axis. The lead here is about 1/1500 of a second.

A third, very significant, lead of the rectified cycle is at the negative maximum, as is seen in the cases of imperfect rectification, oscillograms 2 and 3. Here the lead is a large fraction of a half period.

Oscillogram No. 4, Carborundum. — Oscillogram No. 4, Plate I., was obtained with a carborundum rectifier consisting of a specimen of carborundum, platinized on one side, and held in a clamp under a contact pressure of 3 kg. When sufficient current was sent through the carborundum to give deflections suitable for the oscillogram, the carborundum was overloaded, and permitted current to pass in the negative direction. The carborundum cycle differs from the molybdenite cycle in the absence of lead at the negative maximum and at the point of rising from the zero axis. This anomaly in the case of the carborundum rectifier is seen later to be the effect of its high resistance.

Oscillogram No. 5, Brookite. — The form of the cycle obtained in this case is intermediate between the carborundum cycle and the cycle of oscillogram No. 3. This is consistent with the value of its resistance.

In order to investigate the meaning of the lead of the rectified cycles in the several cases a further examination of the oscillograms is made with the aid of the theory of alternating currents.

Examination of the Oscillograms with the Aid of the Theory of Alternating Currents.

The so-called "voltage-phase cycle" gives the instantaneous values of the current through the deflecting coils and a resistance

chosen to make the amplitude of this current the same as the amplitude of one loop of the current through the rectifier, under the same applied voltage. Although the current of the voltage-phase cycle lags behind the externally applied voltage by an amount depending on the relation of the self-inductance of the deflecting coils to the resistance of the circuit, the current is nevertheless in phase with the voltage immediately about the substituted resistance; for the voltage about a resistance is in phase with the current through it. Now by throwing the switch T of Fig. 6 we put the rectifier in the circuit in the place of the resistance. If the rectifier, when current traverses it, introduces into the circuit electromotive forces out of phase with the current through it, we ought to get a shift of phase of the cycle. We can easily see, for example, that if the rectifier contained capacity or inductance, such a shift would occur. Also, if the action of the rectifier were one of electrolytic polarization, the back E.M.F. of polarization would be approximately determined at any part of the cycle by a time integral of the current, and would introduce a shift of phase resembling that introduced by a capacity.[1]

Also, if the action of the rectifier were due to thermoelectricity, we should expect the thermal electromotive forces developed to be of the form

$$\pm a \int i^2 r dt \tag{1}$$

due to the Joulean heat at the high resistance, and of the form

$$\pm b \int i dt \tag{2}$$

due to the Peltier effect at the junctions. To these terms we should have to add also terms taking account of conduction of heat from the junctions. The term for the conduction of heat would be difficult to assign definite values, but they would be functions of the rise of temperature of the junctions, and may be written in the general form

$$F\left(\int i^2 r dt, \quad \int i dt\right). \tag{3}$$

The terms (1), (2) and (3), when put into the differential equation for the current through the circuit and integrated (if possible), would

[1] B. O. Pierce, Newtonian Potential Function, p. 323, Boston, 1902.

give in the result a shift of phase of the current with respect to the voltage-phase cycle.

Let us, therefore, attempt to determine whether there are any phase differences between the rectified cycle and the voltage-phase cycle that are not accounted for by the conditions existing in the oscillographic apparatus. In doing this we shall make use of the current-voltage characteristic of the molybdenite rectifier, as obtained with the current and voltage in the steady state, and recorded in Table III. and Fig. 5. This table of data was obtained with the same molybdenite rectifier in practically the same adjustment as in the oscillograms 1 and 2 of Plate I.

Let us derive first the numerical equation for the "voltage-phase" curve. In the case of oscillogram No. 1, an ohmic resistance of 400 ohms was in series with the deflecting coils, which had a resistance of 436 ohms, making a total resistance of 836 ohms. Let the inductance of the coils be L. The value of L can be calculated from the voltage and current of the cycle. The R.M.S. voltage impressed on the circuit was 3.54 volts; the maximum voltage was therefore 5.00 volts. The maximum current taken from oscillogram No. 1 was 4.9×10^{-3} amperes, whence we have

$$4.9 \times 10^{-3} = \frac{5.0}{\sqrt{836^2 + L^2\omega^2}}.$$

Therefore

(1) $$L\omega = 584,$$

(2) $$\tan^{-1}\frac{L\omega}{836} = \varphi_1 = 35°,$$

and the equation for the current i_1 of the voltage-phase cycle becomes

(3) $$i_1 = \frac{5.0}{\sqrt{836^2 + 584^2}} \sin(\omega t - 35°).$$

From this equation the values obtained in Table V. were computed, and from these values three half-periods of the voltage-phase cycle are plotted as the sinusoidal curve S of Fig. 7.

The computations when the rectifier is put in place of the 400

TABLE V.

The Voltage-Phase Cycle.

ωt Degrees.	Current in Milliamperes.	ωt Degrees.	Current in Milliamperes.
35	0	135	4.82
55	1.67	155	4.23
75	3.14	175	3.14
95	4.23	195	1.67
115	4.82	215	0
125	4.90		

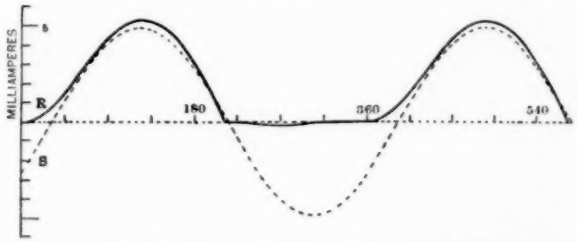


Fig. 7. Rectified cycle computed from the current-voltage values of Fig. 5.

ohm resistance can be made only approximately. The differential equation for the current i_2 through the circuit in this case is

$$E \sin \omega t - e_r = R_e i_2 + L \frac{di_2}{dt}, \tag{4}$$

in which e_r is the drop of voltage about the rectifier, E is 5.0 volts, and R_e the resistance of the deflecting coils = 436 ohms. The drop in voltage e_r about the rectifier is a function of the current. This function is the equation of the current-voltage curve of Fig. 5. It is difficult to obtain an exact analytical expression for this function. But for values of current between 1 and 6 milliamperes, when the current is from copper to molybdenite, e_r is approximately a linear function of the current, with the equation

$$e_r = q + ri, \text{ in which } q = .60 \text{ volt}, r = 183 \text{ ohms}. \tag{5}$$

With this approximation, equation (4) becomes

$$E \sin \omega t - q = (r + R_e) i_2 + L \frac{di_2}{dt}. \tag{6}$$

Integration of this equation gives

$$i_2 = \frac{E}{\sqrt{(r+R_c)^2 + L^2\omega^2}} \sin\left(\omega t - \tan^{-1}\frac{L\omega}{r+R_c}\right) + ce^{-\frac{(R_c+r)t}{L}} - \frac{q}{R_c+r}, \tag{7}$$

in which c is a constant of integration. If we substitute known values in this equation ; namely,

$$\begin{aligned} r + R_c &= 183 + 436 = 619, \\ L\omega &= 584, \\ E &= 5.0, \\ q &= .60, \end{aligned} \tag{8}$$

we have

$$i_2 = 5.87 \times 10^{-3} \sin(\omega t - 43°.3) + ce^{-1.06\omega t} - .97 \times 10^{-3}. \tag{9}$$

For the determination of the constant c we have the relation $i_2 = 0$ when $E \sin \omega t = q$. This gives $c = 5.1$.

From equation (9), values for the current in the upper loop of the rectified cycle for various values of ωt were computed, and are given in Table VI.

TABLE VI.

Computed Values of the Rectified Cycle. Upper Loop.

ωt Degrees.	Current in Milliamperes.	ωt Degrees.	Current in Milliamperes.
0	0	130	5.26
20	.32	140	5.20
40	1.17	160	4.50
60	2.45	180	3.15
80	3.61	200	1.40
100	4.75	213	0
120	5.21		

The lower loop of the rectified cycle was obtained in a similar manner. In this case the drop in potential about the rectifier was obtained from the curve of current from molybdenite to copper of Fig. 5. The equation to this curve, within the limits employed in the calculations, is approximately

(10) $e_r = q_1 + r_1 i_3$, in which $q_1 = 3.8$ volts, and $r_1 = 6470$ ohms.

These values substituted in an equation of the form of equation (7) give, since the exponential term was found to be negligible,

(11) $$-i_3 = .72 \times 10^{-3} \sin(\omega t - 4.8) - .55 \times 10^{-3}.$$

Computations from this equation give the values of current recorded in Table VII.

TABLE VII.

Computed Values of the Rectified Cycle. Lower Loop.

ωt Degrees.	Current in Milliamperes.	ωt Degrees.	Current in Milliamperes.
220	0.00	280	.16
240	.07	300	.07
260	.16	320	.00
270	.17		

The computed values of Tables VI. and VII. are plotted as the continuous curve R of Fig. 7, along with the voltage-phase curve which is the dotted sine curve S.

The data used in the computations are entirely independent of the oscillograms, except that the amplitude of the voltage-phase cycle was taken from oscillogram No. 1 or No. 2, and this value was used in determining the self-inductance of the circuit.

The agreement of the diagram of Fig. 7 with the oscillograms No. 1 and 2 of Plate I. is very striking, as regards both the form and the absolute value of the curves. The agreement with oscillogram No. 2 is a little better than with No. 1, and is within the limit of error of the measurement of the photograph. No departure in amplitude or in phase exists between the rectified cycle and the voltage-phase cycle that is not accounted for by the inductance and resistance of the oscillographic apparatus or by the current-voltage curves of the rectifier with steady currents.

This means that if there are any terms, contingent upon heating or other effects which involves an intergal of a function of the current with respect to the time, this integral attains its final value in a time within the limit of error of measuring the oscillograms, which is about 1/6000 second. This time corresponds to 3.5°, and is about 1 mm. on the original photographs.

It might seem that the approximation made as to the analytical expression for the steady current-voltage curve would not warrant the accuracy here claimed; but if we draw the straight line through the points for which the current is 1 and 6 milliamperes, this line will depart from the observed values only for values of i below 1 milliampere, where the departure will have the following values:

i Millamperes.	Departure. Volts.	Departure in Degrees.
.5	.1	.6
.2	.15	1.7
.1	.3	3.4

In the negative loop of the rectified cycle the departure of the approximation from the observed current-voltage curve is still smaller. However, apart from the specific assumption as to the analytical function representing the current-voltage characteristic of the rectifier under the action of a steady current, the theoretical discussion given above permits a ready qualitative understanding of the lead that occurs in certain parts of the rectified cycle, which may be summarized as follows:

1. The case of the advance of the rectified cycle on rising from the axis of no current is seen to be due largely to the fact that after a dormant half-period the current in the circuit follows the ordinary exponential "building-up" curve for a time before coming into coincidence with the sine curve. This building-up curve starts from the axis with zero lag and is, therefore, in advance of the sine curve. To this effect is to be added the effect due to an apparently higher resistance of the rectifier for small currents than for large currents. This apparently higher resistance brings the building-up curve a little nearer to the sine curve.

2. The slightly quicker descent of the rectified cycle on approaching the axis after having traversed the upper half of the curve is also due to this apparently higher resistance of the rectifier when traversed by smaller currents.

3. The very significant lead of the negative maximum ahead of the corresponding voltage-phase maximum is explicable on the assumption that the rectifier has a much higher resistance in the negative direction than in the positive direction. We have seen above that the angle of lag of the voltage-phase cycle behind the impressed

voltage, determined by the inductance and resistance of the circuit, is

$$\tan^{-1} \tfrac{5}{8}\tfrac{8}{3}\tfrac{4}{6} = 35°,$$

while in the negative direction in order to bring the voltage-phase curve to the same amplitude as the negative maximum of the rectified cycle there would be required a resistance of at least 6,470 plus 436 = 6,906 ohms, whence the angle of lag in this case would be

$$\tan^{-1} \tfrac{5}{6}\tfrac{8}{9}\tfrac{4}{0}\tfrac{}{6} = 4.8°.$$

Therefore the angle of lead of the rectified cycle ahead of the voltage-phase cycle, determined as the difference of these two angles of lag, is 30.2°. This value agrees with oscillogram No. 2.

In this connection it is interesting to notice that a lead of this negative maximum in the case of the carborundum oscillogram does not appear. The explanation of this is easily obtained if one substitutes for the resistance values of the molybdenite the corresponding values for the circuit containing the carborundum rectifier. The equivalent resistance of the carborundum in its positive loop is 6,000 ohms, so that the angle of lag of the voltage-phase cycle with this resistance in it is only 5.6°, while in the negative direction the equivalent resistance of the carborundum is about 20,000 ohms, giving an angle of lag in the neighborhood of 1°. The difference between these two angles of lag, which would give the phase difference between the carborundum cycle and the corresponding voltage-phase cycle would be a quantity just perceptible on the oscillogram, as was verified in the original protographs.

In conclusion of this discussion of the oscillograms, I should say that we have not been able to detect in the photographs any evidence of a thermoelectric or other integrative action of the rectifier.

Thermoelectric Properties of Molybdenite.

In the present section an account is given of the investigation of the thermoelectromotive force of molybdenite against copper, and a determination of the temperature coefficient of resistance of molybdenite. Apart from their possible bearing on the action of the rectifier, these properties of molybdenite are of interest in themselves.

Thermoelectromotive Force. — Five specimens were mounted for

the study of the thermoelectromotive force of molybdenite against copper. These specimens are referred to as *A*, *B*, *C*, *D*, *E*. The method of mounting the specimen *E* is shown in

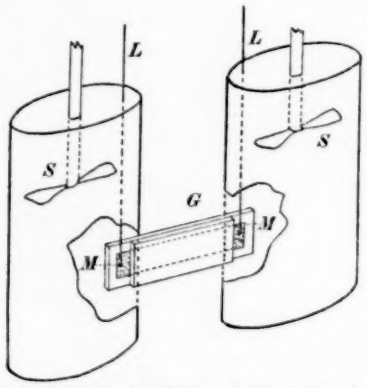


Fig. 8. Apparatus for determining thermoelectromotive force of molybdenite against copper.

Fig. 8. A thin sheet of molybdenite .1 or .2 mm. thick, 2 cm. wide, and 8 cm. long, was cemented between two glass microscope

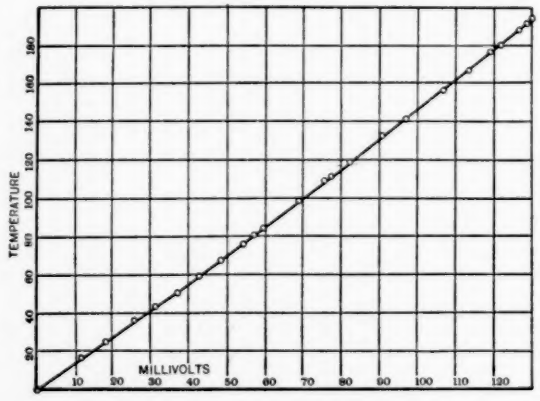


Fig. 9. Thermoelectromotive force of copper-molybdenite couple *E* for various temperatures of hot junction. Temperature of cold junction 0° C.

s des *G* with a cement made of water glass and calcium carbonate.[1] The molybdenite was then copper-plated over a small area at each

[1] Otto Reichenheim suggests the use of such a cement in Inaugural Dissertation, Freiburg, 1906.

of the exposed ends *MM*, and to these copper-plated areas were soldered copper wires, .2 mm. in diameter, so as to form thermal junctions with the molybdenite. The thermal junctions and the ends of the glass mounting were inserted into two brass vessels for containing the temperature baths of oil. The joints between the brass vessel and the glass mounting were made tight with the cement of water glass and calcium carbonate. The oil-baths were provided with stirrers driven by a motor. One of the baths was kept at 0° C., and the other bath was given various temperatures between 0° and 200° C. The resulting thermoelectromotive force was measured by means of a potentiometer to which the copper wires *LL* led. The results are recorded in Table VIII., and plotted in the curve of Fig. 9.

TABLE VIII.

Thermoelectromotive Force of the Copper-Molybdenite Couple, "E" the Cold Junction being kept at Zero.

Temperature of Hot Junction.	E.M.F. in Millivolts.	Temperature of Hot Junction.	E.M.F. in Millivolts.	Temperature of Hot Junction.	E.M.F. in Millivolts.
10.1	− 7.5	59.2	−42.5	133.2	− 90.7
14.3	−10.7	67.4	−48.6	141.9	− 96.9
16.2	−11.5	70.8	−51.2	156.8	−106.8
18.7	−13.8	76.0	−54.1	166.9	−113.2
21.5	−16.0	80.8	−57.2	176.8	−119.0
24.1	−17.6	99.2	−68.4	179.0	−120.0
25.6	−18.5	109.3	−75.2	180.9	−121.5
33.1	−24.6	111.6	−77.2	188.5	−126.2
36.2	−25.9	116.3	−79.2	192.7	−128.7
41.9	−31.5	118.7	−83.2	195.0	−130.0
51.1	−36.7				

The negative sign before the E.M.F. in Table VIII. indicates that this specimen of molybdenite is thermoelectrically *negative* with respect to copper; that is to say, the current at the hot junction flows from the molybdenite to copper.

A slightly different form of mounting was employed for specimens *A*, *B*, *C* and *D*. These specimens, which were cut from two different large crystals of molybdenite, were each 1 cm. wide, 5 cm. long and from .5 to 1 mm. thick, and were mounted in corks. Each cork 4.5 cm. long, was split lengthwise, and one of

the longitudinal half-corks was grooved out to contain the molybdenite. The two half-corks with the molybdenite between were put together again and cemented with plaster of Paris, so as to leave 2 or 3 mm. of molybdenite protruding from each end of the cork. These small areas were then copper-plated, and copper wires .2 mm. thick were soldered to the copper-plated areas, so as to form thermal junctions. The four corks containing the specimens *A*, *B*, *C* and *D* were inserted in round holes in two copper vessels for containing the temperature baths of oil, so that the junction at one end of each specimen should be in the hot bath, while the junction at the other end was in the cold bath. The cold bath was kept at 20°C.; the hot bath was given various temperatures between 20° and 100° C. The thermoelectromotive force of each couple was measured on a potentiometer. The results for *A*, *B*, *C* and *D* are contained in Table IX., and are plotted in Fig. 10. For comparison a part of the curve obtained for *E* is also plotted in Fig. 10.

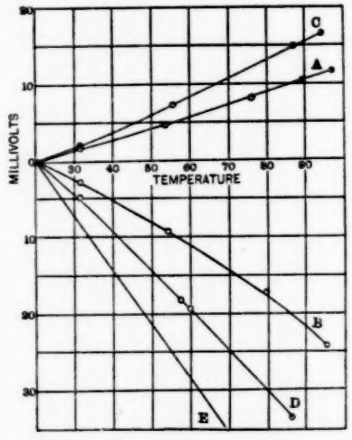


Fig. 10. Thermoelectromotive force of five copper-molybdenite couples, for various temperatures of hot junction. Temperature of cold junction 20° C.

Some of the specimens (*B*, *D* and *E*) are thermoelectrically negative with respect to copper, while the other specimens (*A* and *C*) are thermoelectrically positive with respect to copper. The thermoelectromotive force per degree differs largely with the different specimens, as may be seen by a reference to Table X., which con-

TABLE IX.

Molybdenite-Copper Junctions A, B, C, D. The Cold Junction was at 20° C. The Hot Junction was at Temperature T° C. The Thermoelectromotive Force V is in Millivolts.

Junction *A.*		Junction *B.*		Junction *C.*		Junction *D.*	
T	*V*	*T*	*V*	*T*	*V*	*T*	*V*
31.9	1.45	31.6	− 2.70	31.7	2.01	31.6	− 4.81
53.5	4.63	54.1	− 9.21	55.2	7.20	57.5	−17.9
76.6	8.21	80.0	−17.1			59.8	−19.4
89.4	10.4	87.4	−20.0	87.2	14.9	86.7	−33.7
97.1	11.5	95.3	−24.2	94.4	16.6		

tains the thermoelectromotive force per degree of the different specimens of molybdenite against copper, and against lead (obtained from the known value of the lead-copper junction). For comparison, Table X. also gives the thermoelectromotive power of some other remarkable thermoelectric elements.

TABLE X.

Substance.	Thermoelectromotive Force in Microvolts per Degree Centigrade, at 20° C.		Authority.
	Against Copper.	Against Lead.	
Molybdenite A.	110	113	Present experiment.
B.	−230	−227	" "
C.	175	178	" "
D.	−415	−413	" "
E.	−720	−717	" "
Silicon.		−400	Frances G. Wick.[1]
Bismuth.		− 89	Matthiessen.[2]
Antimony.		26	"
Tellurium.		502	"
Selenium.		807	"

The comparison shows that these specimens of molybdenite have very large thermoelectromotive force against copper or against lead. The specimens *D* and *E* were found to be at the extreme negative end of the thermoelectric series.

The great variability among the specimens studied may be due to an admixture of small quantities of some other substance with

[1] PHYS. REV., Vol. 25, p. 390.

[2] Everett, Units and Physical Constants.

the molybdenite, or it may be due to structural differences from point to point of the crystal. I have not yet investigated the question of the cause of the variability of the phenomenon. The differences in the specimens could not have arisen from the copper-plating or from the heat employed in soldering the junctions, because the specimens *A*, *B*, *C* and *D* were tested before the copper-plating and soldering were done, and by means of the preliminary test were classified as positive, negative, positive and negative respectively; which agrees with the determination after soldering.

The preliminary test was made by touching the specimens with two copper wires connected to a galvanometer, one of the wires being slightly warmer than the other. This preliminary test proved very interesting in that it shows that one may find all over many of the pieces cut from a crystal of molybdenite points where the substance is thermoelectrically positive and other points where it is thermoelectrically negative. These positive and negative points sometimes lie so near together that with a fine-pointed exploring electrode connected to a galvanometer and warmed by heat conducted from the hand one may find the deflections of the galvanometer reversed from large positive values to large negative values on making the slightest possible motion of the pointer over the crystal.

Explorations of this kind failed to show any definite orientation of the thermoelectric quality with respect to the crystallographic axes.

The existence of small thermoelectrically positive and negative patches in a piece of the molybdenite may indicate that the thermoelectromotive force measured by attaching wires to the specimen is too low on account of the inclusion under the electrodes of both positive and negative areas which would partially neutralize the thermoelectric action against another electrode. It may be, therefore, that the contact electrode as it is employed in the use of the molybdenite as a rectifier would be subjected to much larger thermoelectromotive forces than those revealed in the soldered connection experiments.

It may be said in passing that the specimens *D* and *E*, with the soldered connections, still showed the phenomenon of rectification when used with alternating currents, even when the two junctions

of the copper with the molybdenite were in oil-baths at the same temperature as the room and the oil in the baths was vigorously stirred with motor-driven stirrers. The rectification in this case was, however, very imperfect.

Temperature Coefficient of Resistance. — Another interesting thermal property of the molybdenite is its temperature coefficient of resistance. A preliminary report on this coefficient is here given. Two specimens of the molybdenite were made into the form of resistance thermometers, by depositing heavy copper-plated areas near the two ends of thin pieces of the molybdenite and soldering thin copper strips to the copper plate. For insulation a thin strip of mica was placed over the molybdenite, and one of the copper leads was bent back over the mica so that both leads ran away parallel with the mica insulation between. The whole conductor was then placed between two mica strips and inserted in a flattened brass tube. The tube was then mashed tight together so as to securely clamp the molybdenite and its leads. The end of the tube adjacent to the molybdenite was soldered up. The leads were brought out at the other end of the tube and connected to binding posts insulated by a hard rubber head from the tube.

The two molybdenite resistances thus mounted are called No. 50 and No. 51. The dimensions of the molybdenite used in No. 50 were not recorded. The molybdenite in No. 51 was .65 cm. wide by .7 cm. long; the thickness was about .3 mm.

The resistances of these two conductors were measured at various temperatures with the aid of a Wheatstone bridge. They showed no evidence of rectification. In making the measurements it was necessary to keep the current small so as to avoid electrical heating of the conductors. With successive heatings and coolings the resistance of the molybdenite showed small progressive changes, which, however, after some months, almost disappeared. When the resistance of the two specimens of molybdenite had settled down to a practically steady condition, the values plotted in Fig. 11 were obtained. The curves marked "50" and "51" give the resistance of No. 50 and No. 51 respectively. The ordinates for these curves are at the left margin of the diagram, and are in ohms. The curves "*C* 50" and "*C* 51" are for the reciprocals of the resistance

of No. 50 and No. 51 respectively. The ordinates for these curves are at the right hand margin of the diagram.

Each of the specimens has a large negative temperature coefficient of resistance. With No. 50, for example, the resistance at 93.1° C., is 229 ohms; at 0° C., the resistance is 561 ohms; at — 76°, the resistance is 3,051 ohms; and at the temperature of liquid air, the

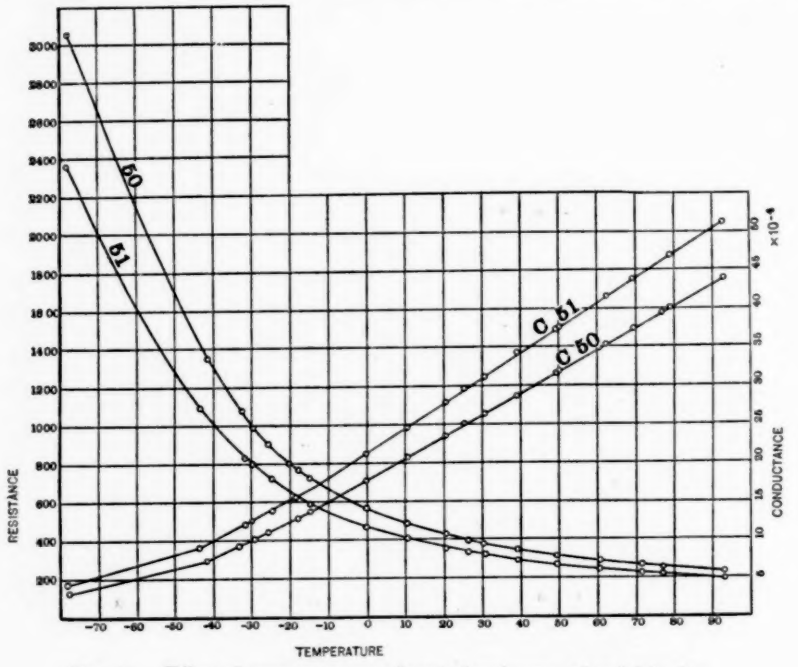


Fig. 11. Effect of temperature on electrical resistance of molybdenite.

resistance of this specimen was found to be over 6,000,000 ohms. This last value is not plotted on the curves.

It is interesting to note that *between — 15° and 93° the temperature-conductance curve of each of the specimens is a straight line.*

At 0° C. the resistance of each of the specimens decreases about 1.53 per cent. per degree centigrade increase of temperature. At 20° the decrease of resistance per degree increase of temperature is 1.19 per cent.

A previous determination of the resistance of molybdenite has been made by Otto Reichenheim.[1] He did not solder on his con-

[1] Otto Reichenheim, Inaugural Dissertation, Freiburg, 1906.

nections but led the current into the specimen through contact electrodes and found that the resistance depended on the contact pressure. His data are, therefore, not comparable with mine, but I find that one of his specimens,[1] measured parallel to the direction of cleavage, gives the conductance a linear function of the temperature between 19.5° and 92.5° C. with a slope not very different from that obtained in the present experiments.

The large thermoeletromotive force of the molybdenite against the common metals, together with its large negative temperature coefficient of resistance, lends plausibility to the hypothesis that the rectification is due to thermoelectricity. For if we pass an electric current through the rectifier and the current begins to make its way through a small area at the contact, this small area is heated and decreases in resistance so that the greater part of the current flows through this particular small area, heating it still more, while the portions of the contact through which the current has not started remain cool and continue to offer a high resistance. The effect of this action is to confine the heating to an extremely small area, which is the condition necessary for the extremely rapid and efficient action of the rectifier. That there is, however, strong evidence against this explanation of the phenomenon is, I think, made clear in the succeeding experiments.

Experimental Facts Adverse to the Thermoelectric Explanation of the Phenomenon of Rectification.

The Thermoelectric Effect Opposite to the Rectification. — A number of experiments with different specimens of molybdenite were made, in which the rectification and the thermoelectric effect could be simultaneously studied. A diagram of the arrangement of apparatus is given in Fig. 12. The specimen of molybdenite is shown at *M* and was held down upon a wooden base by a spring clip. One end of each specimen, which were easily interchangeable in the apparatus, was electroplated with copper at *S*. To this copperplated area a copper lead was soldered. A copper rod *C*, supported as in Fig. 3, was brought into contact with the part of the molybdenite distant from the soldered junction. The molybdenite and the contact

[1] Described as *Stab II.*, p. 27 of the Dissertation.

were put in an electric circuit containing a microammeter or galvanometer at A and a source of variable alternating potential at V. The alternating potential V could be applied or omitted by closing or opening the switch at T. A small heating coil was wound on the rod C, and another similar heating coil E was wound on a second copper rod, placed immediately below the contact of C with M.

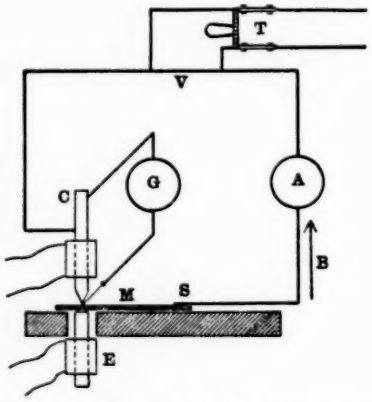


Fig. 12. Apparatus for comparison of rectified current with thermal current.

An auxiliary thermal junction, formed by a small constantan wire attached to the lower end of the copper rod C was connected to a second galvanometer shown at G, for use in a later experiment.

The copper rods C or D could be heated by the surrounding coils, and the thermal current in the circuit through the molybdenite or the circuit through the constantan could be read on the galvanometers A or G. Also the rectified current obtained by applying the alternating voltage V could be read on the galvonometer A. When the thermal current or the rectified current through A is in the direction of the arrow B the molybdenite, following the usage in thermoelectricity, is said to be *positive*. When the current in A is in the direction opposite to the arrow B, the molybdenite is said to be *negative*.

The results obtained with a number of specimens of molybdenite when heat was applied *above*, and when heat was applied *below* and when the *alternating voltage* was applied are contained in Table XI.

TABLE XI.

Sign of Molybdenite, when Heated Above or Below and when Subjected to Alternating Voltage.

Specimen No.	Heated Above.	Heated Below.	Under Alt. Voltage.
75	+	−	−
81	+	−	−
Turned over.	+	−	−
93	−	+	+
Another point.	−	−	+
"	−	−	+
Turned over.	−	−	+
78	+	+	+
Another point.	+	−	−
"	+	+	−
94	−	−	+
Another point.	−	+	+
"	−	+	+

From this table it appears that the thermoelectric voltage *when the junction is heated by heat conducted from above*, in twelve out of the thirteen cases tried, is opposite to the direct voltage obtained when an alternating current is passed through the junction. *When the heat is conducted to the junction from below, through the molybdenite*, the thermoelectromotive force in four cases is opposite to the rectified voltage and in nine cases is in the same direction as the rectified voltage. In only one case, one point of no. 78, is the rectified voltage in the same direction as the thermal voltage both when the junction is heated from above and when it is heated from below.

In all of these cases the heat was applied in the neighborhood of the same junction and there was no opportunity for heat to get to the other junction by conduction, on account of the great distance of the other junction from the source of heat. To make this the more certain this distant junction was in some cases submerged in an oil-bath.

So far as I have been able to learn, this phenomenon of the reversal of the thermoelectromotive force at a junction, conditioned on whether the heat is conducted to the junction through one element of the junction or the other element of the junction is novel. It may be explained by the assumption of another thermal junction of oppo-

site sign in the molybdenite itself below and in the immediate neighborhood of the copper-molybdenite junction. This assumption is plausible because it has been shown above that the molybdenite with which these experiments were performed is thermoelectrically an extremely heterogeneous substance. On the other hand, the phenomenon may also be explained on the theory that the direction of the thermoelectromotive force is determined by the direction of the flow of heat.

Whatever the explanation of the dependence of the sign of the thermoelectromotive force on the manner of applying heat, it is seen that the thermoelectromotive force is usually opposite in sign [1] to the electromotive force produced by sending an alternating current through the junction.

By applying the heat from above and at the same time applying the alternating voltage one can make the thermal current and the rectified current neutralize each other. The opposition of the sign of the rectified current and the thermal current renders the thermoelectric explanation of the phenomenon of rectification highly improbable.

Effort to Detect Heating of the Contact of the Rectifier. — With the aid of the auxiliary thermal junction of copper-constantan placed at the contact of the copper with the molybdenite, as shown in Fig. 12, an effort was made to detect heating of the copper-molybdenite junction by the alternating current which was being rectified. When the rectified current was 118 microamperes, the heating shown by the copper-constantan junction did not exceed .01° C. When on the other hand, as a control experiment, heat was applied to the copper-molybdenite junction from below so as to be conducted through the molybdenite and through the copper-molybdenite junction to the copper-constantan junction, the heating shown by the auxiliary copper-constantan junction was 11.4° C., while the thermal current from the copper-molybdenite junction was only .2 micro-

[1] In a series of experiments with silicon-steel, carbon-steel and tellurium-aluminum, L. W. Austin has found that the rectified current generally flows in opposite direction to that produced by heating the junction. In his experiments (Bulletin of the Bureau of Standards, Vol. 5, No. 1, August, 1908) the heat was applied by a soldering iron brought into contact with the low resistance metal, and therefore corresponds to heat conducted from *above* in these experiments.

ampere. In both the case of the rectified current and the case of the application of heat from below the heat had to be conducted from the point of rectification to the auxiliary junction. Therefore, with a rise of temperature of the auxiliary junction 1,100 times as great as the rise shown during the rectification, the thermal current in the copper-molybdenite circuit was 1/500 of the rectified current; that is to say the rectified current, for a rise of temperature of 1/100 of a degree of the auxiliary junction (being approximately a linear function of the temperature) was less than 1/500,000 of the rectified current from an alternating current producing the same rise of temperature.

From this experiment, also, it seems to the writer that the hypothesis that the action of the rectifier takes place through the intermediation of thermoelectricity is improbable.

The expenses of this research were in part defrayed by a liberal grant from the Bache fund of the National Academy, for which the author wishes to express his sincere thanks.

Experiments are still in progress.

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ATMOSPHERIC RADIOACTIVITY IN CALIFORNIA AND COLORADO AND THE RANGE OF THE α-PARTICLES FROM RADIUM B.[1]

BY FREDERIC A. HARVEY.

THIS paper is an account of an investigation of atmospheric radioactivity at Berkeley California, and Denver, Colorado. The work is of interest in itself, since no previous investigation of this character has been made in these localities; and several new results have also been obtained, including the proof that radium B gives off α-rays of very short range, and the measurement of this range.[2]

The earliest investigations on the subject of atmospheric radioactivity were made by Elster and Geitel.[3] They found that a charged body loses electricity faster in the open air than can be explained by leakage across its supports and that this was due to a slight ionization of the air, which always exists. In the light of the recent discoveries with regard to radioactivity it was seen that this ionization might be caused by some radioactive substance in the atmosphere. To test this they exposed a negatively charged wire gauze in the open air. After an exposure of a few hours the wire gauze was placed in the ionization chamber of an electroscope and it was found that an active deposit had collected on the gauze. The amount of active deposit collected was greatly increased by using a long wire and changing the negative potential from four hundred to several thousand volts. The material of the wire had no effect on the amount of active material collected. The activity decayed in a few hours in a manner resembling that of thorium X. The decay was not hastened by heating. The active deposit could

[1] Submitted in partial satisfaction of the requirements for the degree of Ph.D. in the University of California.

[2] A brief note containing some of the more important points has already been published by the author. Phys. Zeitschr., 1909.

[3] Elster and Geitel, Phys. Zeitschr., 3, p. 76, 1901, and p. 574, 1902; also 4, p. 522, 1903.

be transferred to a piece of leather and when concentrated in this form was sufficiently active to make a barium-platino-cyanide screen glow quite perceptibly to the rested eye, or give a shadow picture through a sheet of aluminium 0.1 mm. in thickness. All of these properties tended to show that the material was of the same nature as the active deposit collected from radium or thorium emanation. The amount of active material collected in caves and holes, where the air had been long stagnant, was much greater than in the open air. Meteorological conditions, such as fog, strong winds, temperature, and barometric height, were found to exert a marked effect on the amount of active material collected.

The work of Rutherford and Soddy [1] on the time rate of decay of thorium X has been extended until it is now generally accepted that each radioactive substance loses its activity according to some exponential law. Thus it is estimated that radium would lose half of its activity in about 1,760 years, whereas, radium A sinks to half-value in only three minutes. Where an active deposit consists of several radioactive components the total activity is made up of the sum of the activities due to these components. The usual method of analysis is to compare the curve showing the rate of decay of the active material with the curves of decay of the transformation products of radium, thorium and actinium, which are known with considerable accuracy. The method is more or less "cut and try" until a combination is found which will make the calculated and experimental results agree.

It is of importance to find the source of the emanation present in the air. Working toward this end Bumstead and Wheeler [2] found that the gas drawn from the surface soil at New Haven contained a radioactive gas apparently identical with radium emanation. Thorium emanation was not discovered because its life is shorter than the necessary time which elapsed in transferring the gas to the testing apparatus. Later Dadourian [3] exposed a negatively charged wire in a hole dug in the ground, at New Haven, into which fresh air was continually drawn from the surrounding soil. He found

[1] Rutherford and Soddy, Phil. Mag., September and November, 1902.
[2] Bumstead and Wheeler, Amer. Jour. Sc., Vol. 17, p. 97, February, 1904.
[3] H. M. Dadourian, Amer. Jour. Sc., Vol. 19, p. 16, January, 1905.

undoubted evidence of thorium emanation in the soil gases. Eve has shown that the amount of radium salts distributed through the earth's crust is of the right order of magnitude to account for the emanation in the atmosphere.

The nature of the emanation which produces the phenomena of atmospheric radioactivity has been the subject of investigation by many observers with apparently diverse results. The usual method is to observe the rate of decay of the active deposit collected on a negatively charged wire exposed in the open air and compare it with the known and different rates of decay of radium, thorium and actinium transformation products. Allen[1] working at Montreal and Cincinnati came first to the conclusion that the emanation is identical with that from radium, but later became convinced, owing to the diverse values of the half-period of decay (viz., the time taken for the decaying radioactive substance to lose half of its initial activity) of the active deposit, that it is a mixture, in varying proportions, of the emanations from radium, thorium and, possibly, actinium. Bumstead[2] showed that the active deposit collected on a wire exposed in the open air at New Haven is complex and that the thorium active deposit sometimes amounts to 15 per cent. of the total. Blanc[3] found that at Rome a very large percentage of the active deposit, from 50 to 70 per cent., collected on a wire exposed at a potential of — 500 volts, was due to thorium transformation products. The exposure in this case was long; nearly three days.

The objects of the present investigation are as follows: (1) To carry out for Berkeley, California, investigations similar to those which have been made in other localities as to the effect of meteorological conditions and as to the nature of the active deposit collected on a negatively charged wire exposed in the open air. (2) To determine the conditions governing the proportion of the components of the active deposit since this proportion was found to be variable. (3) To compare the active deposit obtained at Denver, Colorado, with that obtained at Berkeley. (4) To measure the range of the α-particles given off by the active deposit, particularly the range of

[1] S. J. Allen, Phil. Mag., December, 1904. PHYS. REV., June, 1908.

[2] H. A. Bumstead, Amer. Jour. Sc., Vol. 18, July, 1904.

[3] G. A. Blanc, Phil. Mag., 13, p. 378, March, 1907.

the very easily absorbed radiation and to determine to what component this radiation is due.

The usual method for collecting the radioactive material was used, viz., a wire charged to a negative potential of a few thousand volts, was exposed in the open air for several hours. The wire was of copper, No. 22, B. and S. gauge, about 14 meters in length, supported about four meters from the ground, in the earlier experiments. Later the length was increased to 38 meters, the distance from the ground to about 5 meters, and the wire stretched in a position where winds from all directions could reach it easily. For insulating supports thin ebonite rods, about 40 cm. in length, were used. It was found that in damp weather a thin coating of vaseline put on the hot rods would greatly improve the insulation, as a film of moisture does not collect as readily on the vaseline as on the ebonite. The potential of the wire was maintained at first by means of a water-dropper and later by means of a motor-driven Wimshurst machine, Tudsbury patent. The Wimshurst machine worked more satisfactorily in damp weather than the water-dropper. The potential was measured by means of a Braun electrometer reading directly in volts.

In order to analyze the active deposit it is first necessary to obtain observations which show its rate of decay. This decay, always measured by means of the ionization produced by the α-rays, was followed by several methods :

1. By means of an aluminium-leaf electroscope with sulphur insulation. The rate of fall of the leaf was measured in three ways. (*a*) The image of a circular scale, graduated in degrees, of radius equal to the length of the aluminium leaf, was superimposed on the leaf by means of a half-silvered mirror, placed at an angle of 45° in front of the observing telescope, and readings of the position of the leaf were taken at regular intervals. A curve was then plotted with positions of the leaf and times of observation as coördinates. The tangents to this curve give the rate of fall of the leaf. Any error in reading is self-correcting by this method and tangents can be determined within about one per cent. (*b*) A small Gurley comparator, reading to $\frac{1}{100}$ mm., was used. Readings were taken of the distance moved by the end of the leaf, at about 45° deflection,

during regular intervals of time. (*c*) This method differs from the first only in that a circular scale, with vernier, was fixed to the tube of a telescope and the angular motion of the leaf read by turning the cross wires until one of them coincided with the aluminium leaf. When a very large amount of active material had been collected sufficient accuracy could be attained, without plotting the curve of position, by merely observing the angular fall of the leaf during short, equal intervals of time, from one to ten minutes. The electroscope was calibrated by noting the rate of fall over various parts of the scale when a constant source of ionization, viz., the α-rays from uranium oxide, was used. The deflection of the leaf was kept between the limits 45° and 20°, as over this part of the scale the rate of fall is most uniform. The potential of the charged system for a deflection of 20° was about 500 volts, which was more than sufficient to secure the saturation current for the degree of ionization obtained.

2. By means of a quadrant electrometer made by Max Kohl after the design of Elster and Geitel, which was connected up in the usual way; one pair of quadrants earthed, the other pair connected to a plate or rod in the ionization chamber and the needle charged to a potential of 100 volts. The leak to the quadrants was then measured by noting, with a stop watch, the time taken for the spot of light to travel over a definite number of divisions on the scale — always the same divisions.

3. The null method described by S. J. Allen[1] was used. In this method the unknown ionization is balanced against a known ionization produced by a thin layer of uranium oxide. The parallel plates or concentric cylinders between which is the unknown ionization, are connected to one end of a battery of small cells while the uranium oxide plates are connected to the other end, the middle point being earthed in such a way that the current to one pair of quadrants from the unknown is of opposite sign to that from the standard. The surface of the uranium oxide exposed is varied until these two currents are just equal, when there is no change in the deflection of the needle. The instrument is calibrated for different amounts of surface exposed.

[1] S. J. Allen, Phil. Mag., December, 1907.

The first method was the least subject to external disturbing influences and was sufficiently accurate except when a comparison of the amount of activity of two substances was desired. In consequence it was most used. The other methods, however, were useful as checks. It is not possible to distinguish the curves obtained by one method from those obtained by another.

Percentages of thorium excited activity were determined in the following manner: Several sets of observations on the rate of decay of the active deposit from radium for a three-hour exposure of a negatively charged wire (potential — 5,000 volts or over) to radium emanation in the bell-jar were taken, using the ionization produced by the α-rays. These sets of observations were reduced to a common scale and averaged. From these average values a standard curve was plotted for the rate of decay of an equilibrium mixture of radium A, B and C. The agreement among the several sets of observations was good, the divergence being not more than two or three per cent. in any case. The standard curve was then made to agree with the curve under examination at the thirty-minute point and the activity due to the radium deposit calculated for the three-hour point. Using this value as a first approximation the difference between it and the experimental value gives the activity due to the thorium active deposit at the three-hour point. From this the thorium activity at the thirty-minute point was calculated, using the equation $I = I_0 e^{-\lambda t}$. Thorium active deposit loses half its activity in about eleven hours, hence $I = \frac{1}{2} I_0 = I_0 e^{-11\lambda}$ and $\lambda = .063$ when t, the time, is in hours. The part of the activity due to the radium deposit could now be determined for the thirty-minute point. Using this more accurate value the radium activity at the three-hour point was re-determined from the standard curve, and using the difference between this second approximation and the experimental value as the activity due to the thorium active deposit at the three-hour point the initial amount was determined. This divided by the total initial activity gave the percentage of thorium excited activity to a very close approximation. Correction for the normal leak of the electrometer or electroscope was of course made in each case. When observations had been carried on over a length of time as great as eleven hours the amount of thorium excited activity could be at

once determined, since usually all of the radium excited activity disappears within six hours from the time of ending the exposure. Calculations by the first method showed very good agreement with those by the second.

OBSERVATIONS MADE IN BERKELEY.

The half-value period of the active deposit obtained on a negatively charged wire exposed in the open air was not constant, but varied between wide limits. In particular (see Table I.) the half-period varied from 33 minutes to 5½ hours. As will be shown later the active deposits can be accounted for on the supposition that they consist entirely of radium and thorium transformation products and this change in the period is due to the varying proportions of the components. It takes a little over three days for the thorium active deposit, which will collect on a negatively charged body to reach its maximum value, provided all the conditions are constant during this interval, which is impossible in an open air exposure, and the period will increase with the percentage of thorium deposit. Thus the period depends to a certain extent upon the time of exposure.

This variation of the half-period has also been observed by S. J. Allen.[1] A large part of the present investigation had been completed before Allen's work appeared. The agreement at the two localities is good except that the period varies between wider limits at Berkeley, an effect due to two causes. The present method allows that observations be commenced sooner after the discharge of the wire than does that of Allen. This makes it possible, at times, to observe the activity due to the very rapidly decaying radium A and consequently shortens the period observed. Greater percentages of thorium active deposit must account for the extension of the other limit.

The agreement between the calculated values, assuming that the excited activity is due to radium and thorium and the observed values, is very good. After the percentage of thorium active deposit initially on the wire had been calculated, according to the method described above, the curve $I = I_0 e^{-\lambda t}$ was plotted, where

[1] S. J. Allen, PHYS. REV., Vol. 26, p. 483, June, 1908.

TABLE I.

No. of Curve.	Half-Period.	Per cent. of Th Initially.	Time of Exposure.	Potential.	Remarks.
1	44 min.	1.8	3½ hrs.	3,300	Clear, light east wind, dry. Barom. steady, nearly logarithmic.
2	47 "	3.0	4 "	3,300	ditto.
3	43 "	4.0	3 "	3,600	North wind, clear, hot, very dry, nearly logarithmic.
4	34 "	6.0	3 "	5,000	North wind.
5	72 "	12.8	12¾ "	4,000	North wind, over-night exposure, with strong wind.
6	58 "	12.8	14½ "	4,000	ditto.
7	48 "	22.0	3 "	3,800	Light west wind.
8	66 "	19.0	4 "	3,250	Light southwest wind, very clear, absolutely logarithmic.
9	89 "	46.0	5¼ "	3,500	Light west wind, clear.
10	54 "	32.0	3 "	4,500	Strong west wind, clear.
11	49 "	21.0	3 "	4,500	Light north wind, good logarithmic curve.
12	60 "	11.0	3 "	4,800	ditto.
13	66 "	29.4	12 "	4,000	North wind, strong.
14	59 "	13.0	3 "	4,500	Still, clear.
15	61 "	34.0	13 "	>5,000	Clear, west wind, light.
16	36 "	26.0	4⅓ "	4,500	Cold and foggy, west wind strong.
17	4 hrs.	56.0	13 "	1,500	Cold and foggy, barom. low and falling.
18	44 min.	3.8	3 "	5,000	Same, except barom. rising rapidly.
19	45 "	2.7	3 "	5,000	ditto.
20	51 "	11.6	3 "	1,700	Cold, damp, still.
21	43 "	7.2	3 "	4,000	ditto.
22	90 "	?	12 "		Exposure with A.C. 2,200 volts.
23	56 "	9.2	18 "	>5,000	North wind, very dry.
24	36 "	7.5	12 "	>5,000	ditto.
25	5⅔ hrs.	70.3	22 "	500	ditto.
26	50 min.	11.7	4¾ "	4,000	Just after north wind.

$\lambda = .063$ and t is expressed in hours. This gives the decay of the part of the activity due to the thorium deposit. From the standard curve for the decay of radium A, B and C, in an equilibrium mixture the decay of the part of the curve due to radium active deposit was then determined, making the calculated and experimental values agree at the thirty-minute point. The thorium and radium excited activity decay curves were then added together and in prac-

Table II.

		0	½	1	1½	2	3	6	11	18	24
1	I	182	110	64	35	15	2				
	II	6	5.5	5.5	5	5	5				
	III	188	115.5	69.5	40	20	7				
	IV	188	116	61	33	16	6				
2	I	185	113	70	37	21	2.5				
	II	5.5	5	5	4.7	4.5	4				
	III	190.5	118	75	41.7	25.5	6.5				
	IV	190.5	118	70	41	24	7				
3	I	260	160	90	46	30					
	II	10	9.5	9	8.5	8					
	III	270	169.5	99	54.5	38					
	IV	270	170	100	56	37					
4	I	160	88	40	22	6					
	II	10	9.8	9.6	9.3	9					
	III	170	97.8	49.6	31.3	15					
	IV	170	94	47	27	14					
5	I	164	117	69	31	15	6	?	0	0	0
	II	24	23	22	21.5	21	19	17	12.3	6.7	5.0
	III	188	140	91	52.5	36	25	=	12.3	6.7	5.0
	IV	188	130	83	58.0	40	28	20	12.3	6.7	4.0
6	I	150	90	53	30	12	7	?	0	0	0
	II	22	21	21	20	20	19	15	11	6	4.8
	III	172	111	74	50	32	26	=	11	6	4.8
	IV	172	110	71	54	40	28	16	11	6	4.8
7	I	138	67	41	23	12	6				
	II	39	38	38	37	36	35				
	III	177	105	79	60	48	41				
	IV	177	105	77	58	48	41				
8	I	190	128	80	48	24					
	II	46	44	43	42	40					
	III	236	172	123	90	64					
	IV	236	168	124	90	64					
9	I	85	56	36	20	10					
	II	73	71	68	66	64					
	III	158	127	104	86	74					
	IV	158	127	108	91	73					
10	I	127	61	39	27	11					
	II	46	44	43	42	41					
	III	173	105	82	69	52					
	IV	173	106	82	61	51					
11	I	153	87	54	30	15					
	II	40	39	38	37	36					
	III	193	126	92	67	51					
	IV	193	127	89	66	50					

TABLE II. — *Continued.*

		0	½	1	1½	2	3	6	11	18	24
12	I	53.4	37	23	13	7	2				
	II	6.6	6	6	6	5.5	5.5				
	III	60	43	29	19	12.5	7.5				
	IV	60	44	30	19	13	8				
13	I	110	66	40	21	11	4	?	0	0	0
	II	46	45	43	42	41	39	32	24	14	11
	III	156	111	83	63	52	43	=	24	14	11
	IV	156	109	82	64	54	45	32	23	14	9
14	I	261	172	126	63	39	8				
	II	39	38	36	35	34	30				
	III	300	210	162	98	73	38				
	IV	300	210	148	100	73	36				
15	I	173	93	55	32	17	4				
	II	97	94	91	88	86	80				
	III	280	187	146	120	103	84				
	IV	280	187	141	117	103	85				
16	I	210	82	50	30	14	5			0	
	II	74	72	69	67	65	61			21	
	III	284	154	119	97	79	66			21	
	IV	283	160	116	94	80	70			28	
17	I	43	27	18	11	6	2	?	0	0	0
	II	55	54	53	50	48	45	37	28	18	11
	III	98	81	71	61	54	47	=	28	18	11
	IV	98	81	71	63	56	47	37	28	20	14
18	I	190	111	65.5	32	17.5	8				
	II	7.5	7	6.5	6	5.5	5				
	III	197.5	118	72	38	23	13				
	IV	197	118	68	38	24	13				
19	I	214	136	76.5	59	35	15				
	II	6	6	5.5	5	5	5				
	III	220	142	82	64	40	20				
	IV	220	142	82	64	40	20				
20	I	152	88	54	30	16	6				
	II	20	20	18	18	16	16				
	III	172	108	72	48	32	22				
	IV	172	112	82	54	36	25				
21	I	154	90	56	34	19	4				
	II	12	12	11	11	11	10				
	III	166	102	67	45	30	14				
	IV	166	102	66	44	31	15				
23	I	99	57	36	18	4	2	?	0		
	II	10	10	10	9	9	9	8	5		
	III	109	67	46	27	13	11	=	5		
	IV	109	67	43	26	13	11	8	6		

TABLE II. — *Continued.*

		0	½	1	1½	2	3	6	11	18	24
24	I	185	83	55	31	14	3	?	0		
	II	15	14	14	13	12	12	9	7.5		
	III	200	97	69	44	26	15	=	7.5		
	IV	200	97	62	40	26	14	9	7.5		
25	I	64	45	33	22	8	2	?	0		
	II	151	145	135	132	130	124	103	75		
	III	215	190	168	154	138	126	=	75		
	IV	215	190	170	155	142	127	103	75		
26	I	468	280	174	101	47	14	0	0		
	II	62	60	56	53	51	48	40	32		
	III	530	340	230	154	98	62	40	32		
	IV	530	340	230	154	98	60	40	32		

tically all cases the agreement with the observed values is closer than the limit of experimental error.

Table II. shows the agreement between the observed and calculated results. The number at the head of each column refers to the time, in hours, from the end of the exposure. The number at the left of each set of four rows refers to the number of the observation. The Roman numerals are as follows in each case: I. is the ionization due to the radium products; II. is that due to the thorium products; III. is the sum of I. and II. and gives the calculated activity; IV. is the observed activity. A few curves are given for illustration (see Figs. 1–8, illustrating observations 5, 6, 11, 12, 17, 18, 19 and 21 respectively).

The percentage of thorium excited activity varies between very wide limits (see Table I.), the minimum obtained being 1.8, the maximum 70.3 per cent. of the total activity. The following general statements may be made regarding the conditions governing the percentage of thorium excited activity.

1. A much larger percentage of thorium excited activity collects on a wire exposed at a low potential than on one exposed at a high potential in the open air. This point has been thoroughly tested. Rows 20 and 21 of Table I. are a fairly good illustration of this although here the potential was not varied greatly. The results shown in row 20 were obtained when the potential was — 1,700

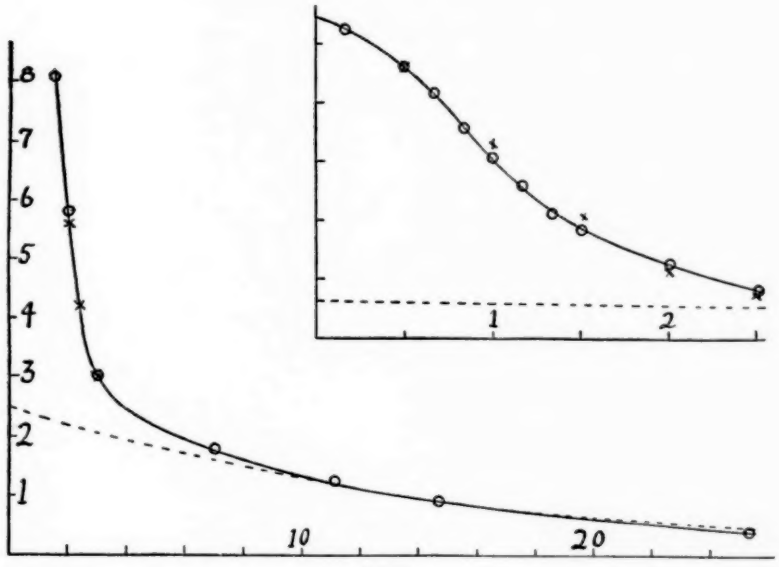
8
7
6
5
4
3
2
1
10
20
1
2

Fig. 1.

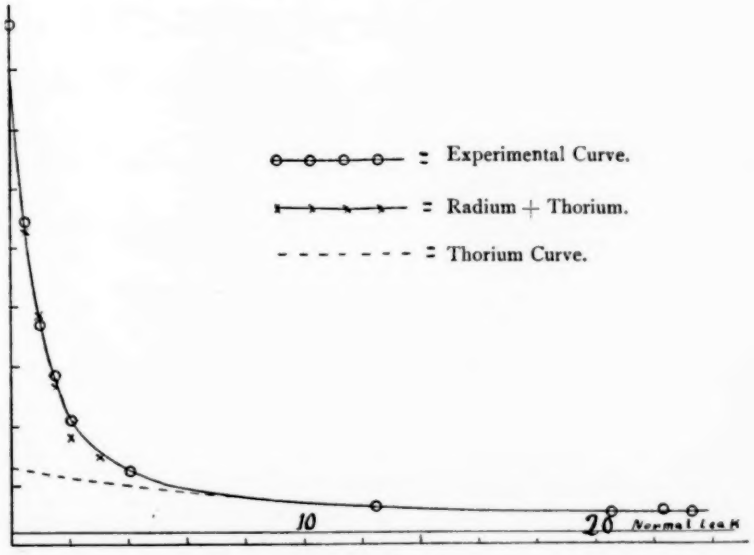
= Experimental Curve.
= Radium + Thorium.
= Thorium Curve.
10
20
Normal Leak

Fig. 2.

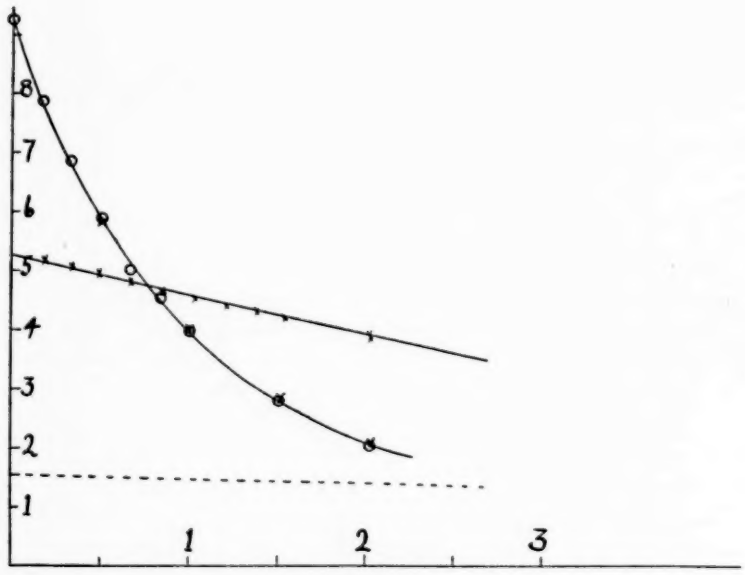

Fig. 3.

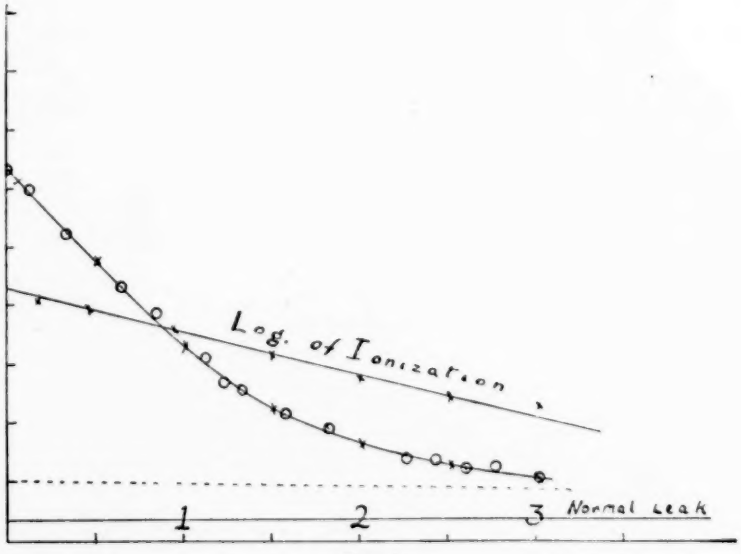

Fig. 4.

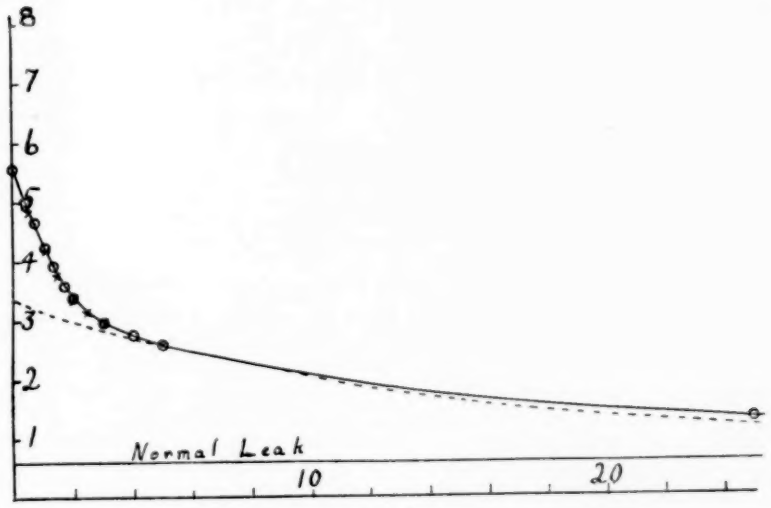
8
7
6
5
4
3
2
1
Normal Leak
10
20

Fig. 5.

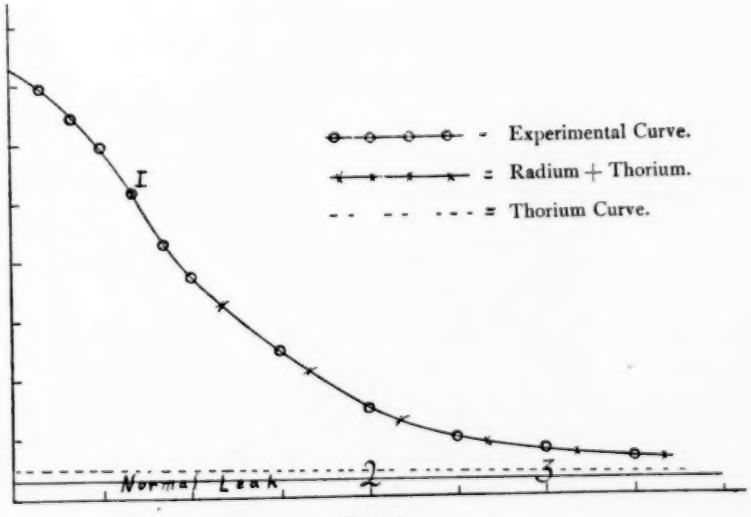
Experimental Curve.
= Radium + Thorium.
= Thorium Curve.
I
Normal Leak
2
3

Fig. 6.

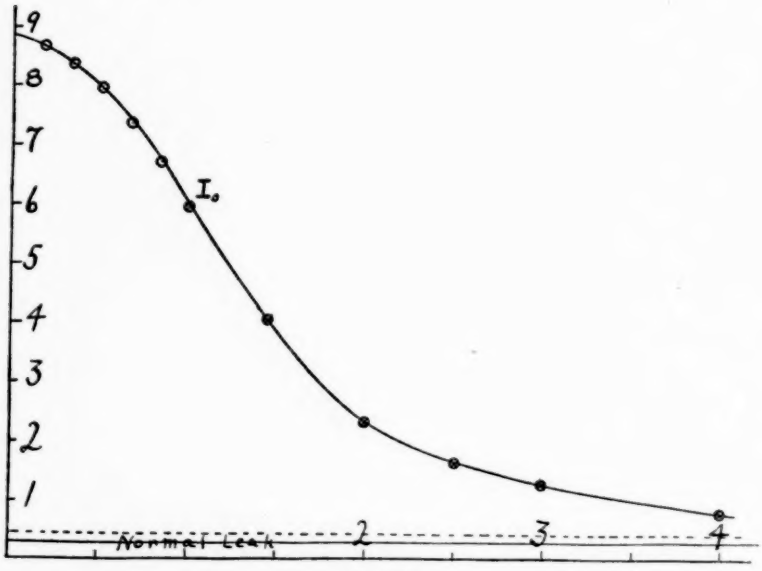

Fig. 7.

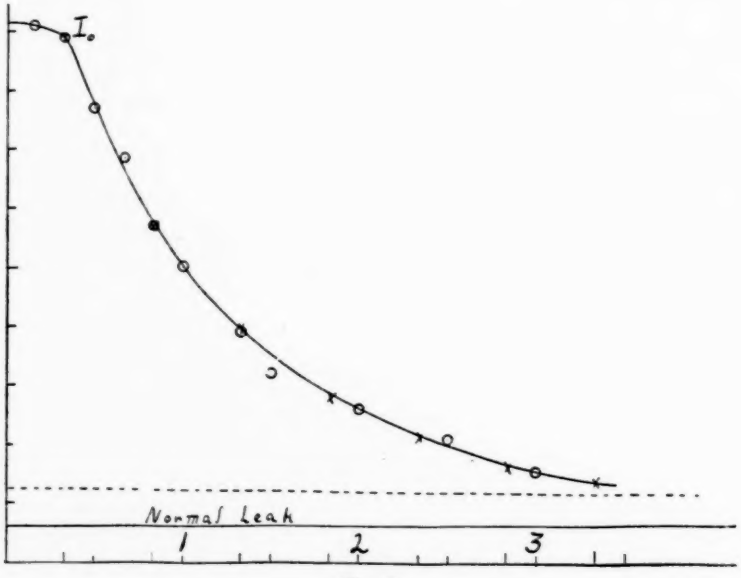

Fig. 8.

volts, in row 21 when it was — 4,000 volts. Atmospheric conditions were identical in the two cases and the two exposures occupied a total time of only seven and a half hours. Row 20 shows 11.6 per cent., row 21, 7.2 per cent. of thorium excited activity. Row 17 shows an unusually high percentage. The low potential, — 1,500 volts is partially responsible for this although here other conditions combine to cause the high percentage (see below). Row 25 which shows the highest observed percentage, 70.3 per cent., of thorium deposit is perhaps the most striking example. The observations shown in this row were taken under conditions very similar to those of row 23 and 24, *i. e.*, during a north wind, when a low percentage would be expected (see below). The potential was very low, being only — 500 volts. The time of exposure was long but not greatly longer than that of the wire in observation No. 23.

This fact contains the explanation of the very large percentages, from 50 to 70 per cent., of thorium excited activity obtained at Rome by Blanc,[1] who used a potential of only — 500 volts. It has long been known that this is not a sufficiently high potential to collect the maximum amount of active deposit on a wire exposed in the open air. These percentages, it is true, were obtained with very long exposures, and it takes a little over three days for the thorium active deposit to reach 99 per cent. of its final value. It is a very simple matter however to calculate the final per cent. of thorium deposit, which would have been collected on the wire had equilibrium been reached, from the time of exposure and the observed percentage. Moreover this is a much more reliable method as it is very unlikely that the percentage of thorium excited activity would not change during a three-day exposure and this would produce irregularities in the curve which would militate against accuracy. In Table III. the calculated percentage of thorium excited activity, had it reached an equilibrium is given under the heading per cent. Th. Corrected, and it is here conclusively shown that there is a very wide variation in the actual proportion of thorium excited activity to be collected from the atmosphere at different times, the minimum being 10.6 per cent., (row 24) and the maximum 76 per cent. (row 9). Sixteen out of the twenty-six values fall below the minimum set by

[1] G. A. Blanc, Phil. Mag., 13, p. 378, March, 1907.

TABLE III.

No. of Curve.	Hours of Exposure.	Total Activity.	Due to Ra.	Due to Th.	Ra Corrected.	Th Corrected.	Total Corrected.	Per Cent. Th Corrected.	Barom.
1	$3\frac{1}{2}$	188	182	6	190	30	220	13.6	Steady.
2	4	190.5	185	5.5	191	25	216	11.5	"
3	3	270	260	10	271	59	330	17.8	
4	3	170	160	10	167	59	226	26.5	Rising.
5	$12\frac{3}{4}$	188	164	24	164	44	208	21.2	
6	$14\frac{1}{2}$	172	150	22	150	39	189	20.6	Falling.
7	3	177	138	39	144	230	374	61.5	"
8	4	236	190	46	196	209	405	51.6	
9	5	158	85	73	86	270	356	76	
10	3	173	127	46	133	270	403	67	
11	3	193	153	40	202	235	437	54	Steady.
12	3	60	53.4	6.6	63	39	102	38.2	"
13	12	156	110	46	156	87	243	35.6	"
14	3	300	261	39	272	230	502	46.0	"
15	13	280	173	97	173	173	346	50.0	"
16	$4\frac{1}{4}$	284	210	74	216	308	524	59.0	
17	13	98	43	55	43	97	140	69.3	Low and falling.
18	3	197	122	7.5	127	44	171	25.7	Rising rapidly
19	3	220	214	6	223	35	258	13.6	ditto.
20	3	172	152	20	158	118	276	42.8	Falling slightly.
21	3	166	154	12	160	70	230	30.2	Steady.
23	18	109	99	10	99	19	118	16.1	Steady.
24	12	200	185	15	185	22	207	10.6	Rising.
25	22	215	64	151	64	198	262	75.8	"
26	$4\frac{3}{4}$	265	234	31	238	120	358	33.6	Steady.

Blanc, viz., 50 per cent. I think that without doubt the lower value of the percentage of radium emanation given by Blanc, for Rome, compared with that by Dadourian[1] for New Haven is due to the fact that Blanc did not use sufficiently high potentials, rather than the difference in locality.

An explanation of the cause of the higher percentages of thorium excited activity with low potential is somewhat difficult owing to the imperfect state of our knowledge as to the actual mechanism of the collection of the active deposit on a negatively charged wire; *i. e.*,

[1] H. M. Dadourian, Amer. Jour. Sc., 25, p. 335, April, 1908.

why, when the neutral emanation expels a positively charged α-particle it leaves behind a positive instead of a negative charge on the radium A particle. There must be, it would seem, a different rate of diffusion because of which most of the thorium A particles are drawn to the wire for a low potential while it requires a high potential to exhaust the surrounding air of its radium transformation products.

2. The percentage of thorium excited activity is very sensitive to barometric change. Observations 17, 18 and 19, represented by Figs. 5, 6 and 7 furnish a good illustration of this. The potential is, it is true, lower for Fig. 5, but the extreme change from 69.3 to 13.6 per cent. (see Table III.) of thorium deposit is not all accounted for by this difference. Observations 17 were taken just at the end of a long continued barometric fall, 18 and 19 immediately afterward when the barometer was rising rapidly. The percentage decreases from observations 18 to 19, although one was taken immediately after the other and conditions were exactly similar. This plainly shows the decrease of thorium excited activity during a rapid rise in the barometer. It is to be expected if we suppose the emanation to diffuse upward through the soil. An increase of pressure would tend to prevent the escape of the emanation into the air and as its period is so short, 54 seconds, the supply of thorium A would be cut off at once and the only active products which it would be possible to collect would be the thorium A, B and C already present in the atmosphere. These would of course be decreasing all the time. The radium emanation, half-period 3.7 days, on the other hand, would persist much longer and keep up the supply of radium A. It is thus clear why the percentage of thorium active deposit is decreased by a sudden rise in the barometric pressure.

3. Another fact of interest for comparison is the following: D. Pacini,[1] finds for a wire exposed over the Gulf of Liguria, for nine hours, that practically all the activity is due to radium, with scarcely a trace due to thorium. At Berkeley the west wind sweeps directly in through the Golden Gate, over the Bay of San Francisco and over about 2.4 miles of land to the Physics building, yet the percentages of thorium excited activity are much larger for this wind than for

[1] D. Pacini, N. Cimento, 15, p. 24, January, 1908.

any other. The average of the equilibrium values of the per cent. of thorium excited activity, from Table III., for exposures 7, 8, 9, 10, 15 and 16, which were made during periods of west wind, is 60.8 per cent. The average of all other percentages except those from north wind exposures 37.9 per cent. The average of all percentages except for west wind exposures is 31.7 per cent. These percentages prove that either the air over the Pacific Ocean off San Francisco, does contain thorium emanation or that the West Berkeley tidal-marshes have an unusually high percentage of thorium salts. Opportunity has not yet presented itself to test the two possibilities.

The initial activity on the wire varied between very wide limits, the maximum being as much as seventy times the minimum. The greatest amount of active material was collected during a hot, dry, north by east wind. This wind is known in Berkeley as the "north wind" and is the only strong land wind. It attains a velocity of 20 or 30 miles an hour at times. There is a large area covered by volcanic springs, where Shasta, Tehama and Plumas counties, California, come together, about 180 miles from Berkeley. The north wind crosses this area and follows the course of the Sacramento River. It seems very probable that the increased activity, at such times, is due to radium emanation carried down from this region. This supposition is borne out by the fact that the greatest activity does not appear on the first day of the wind, which usually blows three days, and also by the fact that the increase in the activity is very largely due to radium products whereas there is not a corresponding increase in the activity due to thorium products. The short life of the thorium emanation would account for this latter. Table III. does not give the actual initial values of the activity on the wires as it is more convenient to have comparable numbers for the purposes of plotting, etc., but it will be seen that the sets of observations 1 to 6, 23 and 24 show a low percentage of thorium excited activity. These observations were taken during periods of north wind. The results shown by curve 25 apparently present an exception to this as they also were taken at the time of a north wind but here the high percentage is due to the low potential as explained above. The low percentage shown in rows 18 and 19 is also explained above.

The north wind is accompanied by very disagreeable physiological effects and it has been suggested that these may be due to the abnormally large amounts of radium emanation in the air. Experiments on the effect of radium emanation on animal life would be comparatively easy to try and might yield some interesting results.

The north wind is also accompanied by a rise in temperature and low relative humidity. Ordinarily, at Berkeley, the relative humidity varies from 80 to 90 per cent., but at these times it may fall as low as 50 per cent.

The south wind is also a land wind, but is not accompanied by nearly such large amounts of active material. The relative humidity is so high that insulation is maintained with extreme difficulty and measurements hard to make.

The lowest activity accompanies the wind from the west, *i. e.*, from the ocean. Here also the relative humidity is high. The experiments of Elster and Geitel [1] showing that the greatest amount of active deposit was collected during a fog are not borne out at Berkeley. The fog here is not a land fog but is blown in from the ocean and is accompanied by a very low activity. The greatest amount of active material is collected when the relative humidity is low, *i. e.*, when there is a north wind as stated above. Attempts to discover a direct relation between humidity and amount of active deposit have not been successful as might be predicted since too many disturbing conditions enter.

The variation in temperature is so small at Berkeley that no effects due to it have been observed.

The statement is very generally made that "the height of the barometer was found to exert a very marked influence on the amount of excited activity to be derived from the air."[2] This appears to need correction in its statement though not in its interpretation. It is not the actual atmospheric pressure which has an effect on the amount of active material but the history of the barometer for a few hours previous to and during the exposure. It has already been shown that a sudden rise in the barometer will cause a change in the relative amounts of thorium and radium deposits but not very

[1] Elster and Geitel, Phys. Zeitschr., 4, p. 522, 1903.
[2] Rutherford, Radioactivity, second edition, p. 518.

much change in the total amount of material collected. A long continued low barometer usually causes an increase in the amount of active material collected but the north wind, which, as has been said, brings the greatest amount, is almost always accompanied by a steady, high barometer.

It appeared from the earlier experiments that an uncharged wire did not collect a measurable amount of active deposit. This was true for a wire suspended near the Physics building and running parallel to its walls. In the later experiments a wire was stretched across the roadway, near the building, and it was found that considerable quantities of dust were collected. The uncharged wire was therefore tested again after an exposure of some 48 hours and a slight activity detected. This result again agrees with the work of Allen (*loc. cit.*) on the Radioactivity of a Smoke-Laden Atmosphere. It appears that the active particles collect on the dust or smoke particles which in turn collect on the wire. No such large amounts as Allen speaks of were at any time collected. A positively charged wire showed no signs of activity after a twelve-hour exposure. A wire connected to one terminal of a 2,200 volt alternating current circuit while the other terminal was earthed showed more activity than an uncharged wire and less than one charged negatively to the same potential.

In order to determine whether the fact that the wire is charged during an exposure has any effect on the period of transformation of the particles which collect on it the following experiments were tried. Two wires were exposed, side by side, charged to the same negative potential for five hours. At the end of this time they were brought in and the activity of one of them tested. The other was coiled in a convenient shape and hung in a bell-jar of small capacity, where it was maintained at the same negative potential it had when exposed. After two and a half hours its activity was tested and it was found to continue the curve of decay from the earlier wire without discontinuity. The experiment was repeated maintaining the wire when in the bell-jar positively charged, with the same result as for the negative charge. This shows that the charge on the wire does not have any effect on the period of transformation. The result might again have been predicted as, accord-

ing to the theory of radioactive transformations, no force of finite magnitude can alter the period of transformation.

Curves of the shape shown in Figs. 6 and 7, consisting at first of a convex upward part, are very similar to those called class 2 by S. J. Allen (*loc. cit.*). I have found that a curve of this type almost always results from an exposure made while the barometer is rising, and seldom from an exposure made under any other conditions. It is to be expected that a change in the barometric height would cause a change in the supply of emanation and hence a change in the equilibrium value of the mixture of products and hence an irregularity in the shape of the curve.

Observations Made in Denver.

During June and July, 1906, some measurements of the active deposit obtained from the atmosphere were made in Denver, Colorado, and as I am not aware of any published results from this locality they are given here.

The exposed wire was of copper, No. 18 B. and S. gauge about 12 meters in length and three meters from the ground. The potential was maintained by means of a water-dropper. After an exposure the wire was wound in the form of a helix and introduced into an aluminium-leaf electroscope, where the rate of decay was followed by the method 1*a*, described above.

The results do not differ essentially from those obtained at Berkeley except as to the effect of the direction of the wind. The greatest amount of active deposit was collected at the time of a high northwest wind but as this was the only strong wind during the two months over which the observations were extended, the direction cannot be regarded as having any very great importance. The amount of active material collected does not differ appreciably at the two places. Percentages of thorium excited activity and the half-period vary between about the same limits.

The observations were brought to an end by the maturing of the seed-pods on the cotton-wood trees. The blowing of the cotton made insulation a matter of extreme difficulty.

Of the exposures made, nine yielded useful results. The tables corresponding to Tables I. and III. follow.

TABLE D–I.

No. of Curve.	Half-Period.	Per cent. of Th Initially.	Time of Exposure.	Potential.	Remarks.
D–1	90 min.		3 hrs.	4,000	High west wind.
D–2	30 "		3 "	4,500	ditto. Short period due to Ra. A.
D–3	60 "	50	15 "	4,500	Very high northwest wind.
D–4	53 "	27	4 "	4,500	Clear, still.
D–5	55 "	13.7	4 "	3,000	ditto.
D–6	48 "	8.0	3½ "	4,250	ditto.
D–7	45 "	4.0	4 "	4,500	ditto.
D–8	50 "	2.5	3 "	3,700	Cloudy, still.
D–9	33 "	15.0	3¼ "	4,750	Light east wind, clear, short period due to Ra. A.

TABLE D–III.

No. of Curve.	Hours of Exposure.	Total Activity.	Due to Ra.	Due to Th.	Ra Correc.	Th Correc.	Total Correc.	Per cent. Th Corrected.
D–3	15 hrs.	540	270	270	270	440	710	62.0
D–4	4 "	130	95	35	98	159	257	62.0
D–5	4 "	127	109.6	17.4	113	79	192	41.0
D–6	3½ "	180	165.6	14.4	173	72	245	29.4
D–7	4 "	400	384	16	396	73	469	15.6
D–8	3 "	440	429	11	452	65	517	12.5
D–9	3¼ "	380	323	57	334	317	651	48.7

RANGE OF THE α-PARTICLES FROM THE ACTIVE DEPOSIT AND FROM RADIUM B.

It seemed desirable as a further proof that the active deposit collected on a negatively charged wire exposed in the open air consists of radium and thorium transformation products, to test the range of the α-particles. It was thought that the method proposed by Bragg [1] for a feebly active product might be used, for, as has been shown, wires can be obtained with a very low percentage of thorium excited activity and this amount might be calculated and the proper correction made. The method measures the range in terms of the stopping power of a screen of variable thickness covering the active substance. A wire was therefore exposed, the active deposit rubbed off with a piece of absorbent cotton moistened with ammonium hydroxide, a treatment which will further reduce the

[1] W. H. Bragg, Phil. Mag., 11, p. 754, June, 1906.

percentage of thorium active deposit as this deposit is less soluble in ammonium hydroxide than that of radium. The cotton was then incinerated, the residue spread in as thin a layer as possible and its activity tested, first when the ionization chamber was directly exposed to its influence and then as very thin sheets of aluminium foil were placed over it. Readings were frequently taken with the naked deposit to obtain data from which the decay curve could be plotted. The time of all readings was recorded. The result obtained was very unexpected. Fig. 9 plainly shows the presence of a radiation which

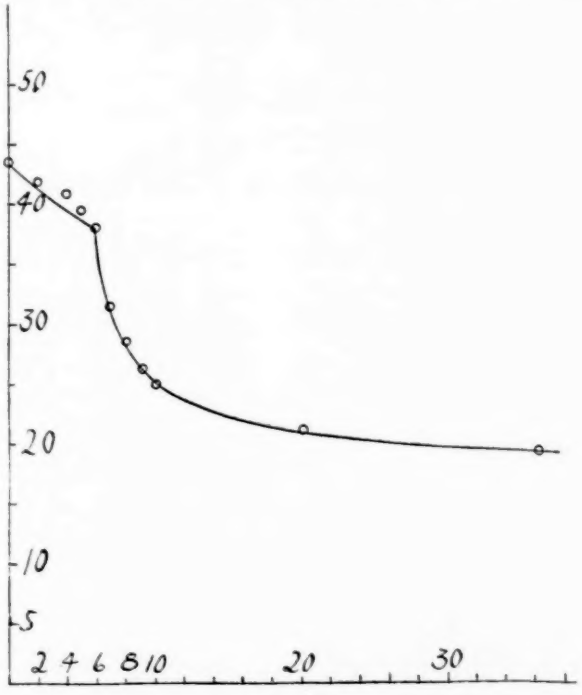

Fig. 9.

is completely absorbed by from 6 to 10 layers of aluminium foil. It is evident at once from the curve that agreement among separate calculations of the full range cannot be expected by Bragg's method. The characteristic shown in the tables given by him, *i. e.*, an increase in the value of the product ρd, *i. e.*, density times thickness, for full range, as the thickness of the foil was increased was shown to a very marked degree. Calculations for the range are all smaller than

would be expected and the calculation from the foil of greatest thickness gives a little less than one half the range of radium C.

The recent work of S. J. Allen[1] explains this value. He has tested the range of the α-rays from the active deposit obtained from the atmosphere and has shown that "where the rays are allowed to emerge in all directions to the normal the position (*of maximum ionization*) is much less than the range of the particle, being roughly one half." The above result is in agreement with this statement by Allen.

The product, ρd, of the foil used to obtain the data for Fig. 9, was 6.47×10^{-5} for each sheet. Using the value of the stopping power of aluminium foil, in terms of air, given by Bragg, viz., foil for which $\rho d = .00329$ is equivalent to 2.30 cm. of air, calculation shows that the easily absorbed radiation would be completely stopped by between 2.7 and 4.5 mm. of air. The values of the stopping power of aluminium foil obtained by S. J. Allen (*loc. cit.*) agree very well with that of Bragg, and show that it is about the same for rays from radium C, thorium and uranium. It is to be seen from Fig. 9 that nearly half of the ionization produced by the naked deposit is due to this easily absorbed radiation. The curve has been corrected for the natural decay of the deposit and the ionization chamber was made deep enough to allow the α-particles from radium C and thorium C to run their full course.

It was of course desirable to determine which of the several components of the active deposit gives off this easily absorbed radiation. To do this, first, a wire was exposed for a long time in the open air in order to obtain a large amount of thorium active deposit. This deposit was allowed to stand for six hours before any tests were made, during which time all the radium products transformed into the inactive radium D. The data for an absorption curve were then obtained by adding layers of aluminium foil and taking readings of the ionization. The absorption curve, corrected for the natural decay, showed no trace of the easily absorbed radiation. The radiation, then, cannot be due to thorium A nor any of its successive transformation products. This result was expected as Fig. 9 shows such a large part of the total ionization to be cut off by the first ten sheets of foil.

[1] S. J. Allen, PHYS. REV., XXVII., p. 294, October, 1908.

A wire was next exposed to radium emanation and the absorption curve obtained as before. The characteristic inflection reappeared. It is not quite so marked as in the case of the atmospheric curve but it is evident that part, if not all, of the easily absorbed radiation comes from radium excited activity.

Four curves were then obtained which were so timed that the inflection point should come at 30, 50, 60 and 140 minutes from the time of discharge of the wire. The point of inflection is most marked in the first, less so in the second, still less in the third and does not appear at all in the fourth. Radium A has all transformed before the beginning of the observations, *i. e.*, in about ten minutes. The activity after about two hours is almost entirely due to radium C. The easily absorbed radiation cannot then be due to either of these and must therefore be due to radium B.

An effort was then made to measure directly the range of this radiation. Two methods of attack at once present themselves. The slit or bundle of tubes necessary to get rid of all except the normal rays may be dispensed with, since the distances used are so very small. Or the pressure of the gas in which the α-rays travel may be reduced to about one tenth atmosphere, when the distances will become large enough for the usual method. The first method was used for two reasons. First, apparatus was at hand with only slight alteration and, second, the radium bromide at present available is so weak as to make it desirable to utilize all the radiation possible. The results give justification for the first method. The apparatus is shown in section in Fig. 10 and does not differ from the ordinary form, used for these measurements, except in two points. First, as has been said, the bundle of tubes limiting the rays which reach the ion-trap to those shot off normally, was dispensed with. Secondly, a sheet of very thin aluminium foil (*B–C*, Fig. 10) was stretched tightly just below the plate *A*, connected with the electrometer. This sheet of foil was equivalent to about 0.5 mm. of air. It prevents the

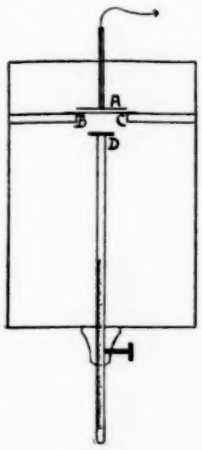

Fig. 10.

diffusion of ions from below and at the same time lets through more α-particles than a wire gauze. The plate A was set as close to the aluminium foil as possible without increasing the capacity of the system so much as to cause a large decrease in sensitiveness. The final distance used was about 7 mm. The plate was about 8

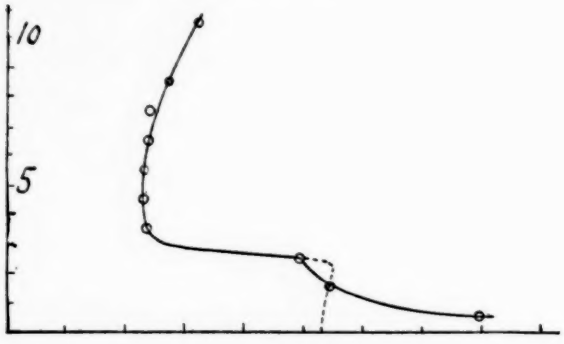

Fig. 11.

cm. in diameter. It is necessary to stretch the aluminium foil tightly as otherwise the attraction between the charged surfaces causes an alteration of the position of the aluminium foil.

The experimental curves obtained, as the distance of the wire, placed on the Table D, below the aluminium foil, was altered, are

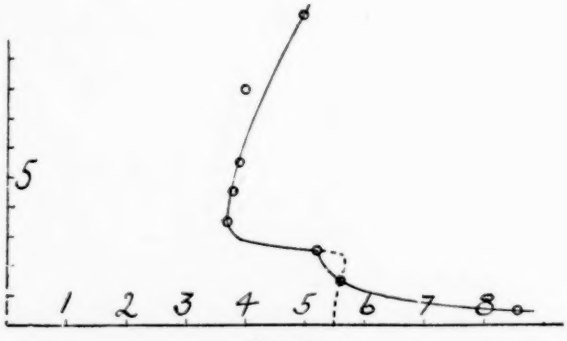

Fig. 12.

of the characteristic shape of those showing the range of α-particles, except at the very lower part (see Figs. 11 and 12). The cause of the departure from the usual, dotted form, is easily explained.

Theory requires that the ion-trap shall be shallow in comparison with the range of the α-particles. This is realized for the upper part of the curve where the α-particles from radium C produce the ionization. Hence the curve takes the usual form for this part, and for the part where the short range particles just begin to reach the ion-trap. As the distance is further diminished however the short range particles produce more and more ionization. When the wire touches the aluminium foil they run their full range and hence produce the greatest ionization. The figures show that the easily absorbed radiation has a range between 2.6 and 3.0 mm. in air under normal conditions. The curves are plotted from the following data, corrected for the natural decay of the active material, and for the absorption by the thin sheet of aluminium foil.

Distance in mm.	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.0	8.5	10.5
Ionization Fig. 11.	800	545	495	267	260	263	290	290		325	375
Ionization Fig. 12.	860	560	520	360	370	380			400		500

Summary.

1. The half period of decay is not constant but varies from thirty minutes to five and a half hours.

2. Agreement between the experimental results and those calculated on the basis of a mixture of thorium and radium products is closer than the limit of experimental error.

3. The percentage of thorium excited activity for an equilibrium mixture varies between 10.6 and 76.0 per cent. of the total.

4. Percentages of thorium excited activity depend upon the following conditions: (*a*) A wire exposed at a low potential, — 500 volts, collects a much larger percentage than one exposed at a high potential, — 5,000 volts or over. (*b*) The percentage is very sensitive to barometric change. (*c*) The west wind is accompanied by the largest percentage, indicating that the air over the Pacific Ocean, off San Francisco, contains thorium emanation or that the tidal marshes over which the wind comes have an unusually high percentage of thorium salts.

5. The greatest amount of active material is collected on days when there is a north wind.

6. Variation in atmospheric pressure and not actual barometric height affects the amount collected.

7. Curves which have initially a convex upward part are obtained when an exposure is made while the barometer is rising.

8. The active deposit obtained at Denver, Colorado, does not differ appreciably from that obtained at Berkeley, California.

9. Results on the range of the α-particles from the active deposit are in agreement with those obtained by S. J. Allen for the long range rays.

10. The short range α-particles given off by the active deposit are due mainly if not entirely to radium B.

11. Nearly half the ionization produced by the deposit obtained from an open-air exposure is due to α-rays which have a range of between 2.7 and 3 mm. in air, under ordinary conditions of temperature and pressure.

In conclusion I wish to thank Professor E. P. Lewis for his unfailing interest and kindness during the course of my investigations.

UNIVERSITY OF CALIFORNIA,
November 15, 1908.

TELEPHONE RECEIVER IMPEDANCE.

By Roy T. Wells.

SEVERAL investigations have been made on the variation of the sensibility of the telephone receiver with the frequency of the current flowing in it. Rayleigh[1] and Wien[2] examined telephones with regard to their current sensibility, measuring the least current that would produce audible sound at different frequencies, and Austin[3] with regard to the volt sensibility, measuring the least impressed electro-motive force that would produce audible sound at different frequencies. A curve of either sort can be converted into one of the other if the impedance of the telephone at the different frequencies is known. Austin in his paper gave the resistance and inductance at 100 and 900 cycles per second.

Since a critical study of the telephone offers one of the promising fields for wireless telegraph development, it has seemed worth while to examine more carefully the variation of resistance, inductance and impedance with frequency.

The method used was to measure the resistance and inductance directly and at the same time by the Maxwell bridge method, as used by the writer in earlier work.[4] No attempt was made to develop the mathematical theory, which would be very complicated. The results, however, might be expected to, and do, agree in a general way with those found theoretically and experimentally for a long solenoid enclosing a conducting core, in the paper by the writer referred to above.

A variable standard of inductance was loaned by Prof. A. G. Webster, of Clark University, and Prof. W. L. Hooper, of Tufts College, opened his laboratory for the work, providing power and

[1] Philosophical Magazine, 38, p. 294, 1894.

[2] Annalen der Physik, 4, p. 450, 1901.

[3] Bulletin of the Bureau of Standards, Vol. 5, No. 1, p. 153, 1908.

[4] Physical Review, Vol. 26, No. 5, p. 337, 1908.

other apparatus. Mr. Munro, of Tufts College, was of great assistance in the work. The current supply was taken from a motor-driven alternator, giving any frequency up 1,000 cycles per second.

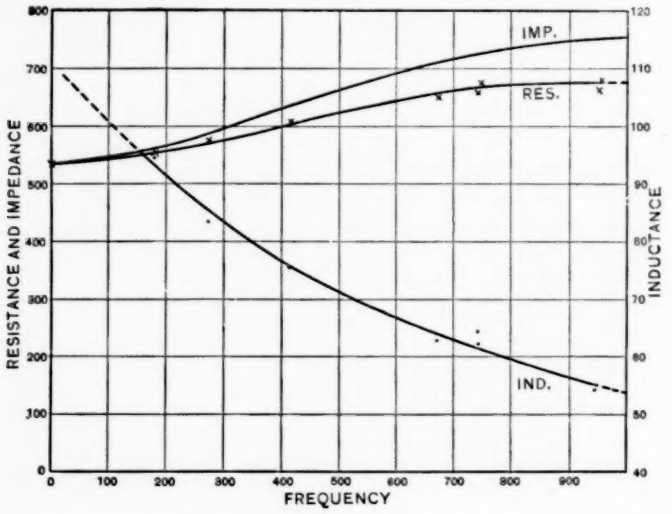

Fig. 1.

Two telephones were examined in detail. No. 1 was one of a pair of head telephones made for use as a wireless telegraph receiver. Its direct-current resistance was 531.6 ohms. No. 2 was a watch

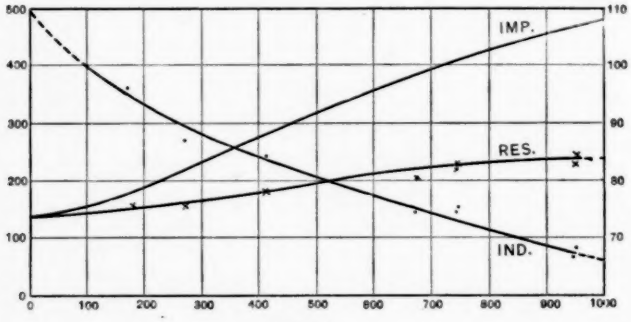

Fig. 2.

case receiver, picked out at random in the Tufts College apparatus room. Its direct-current resistance was 132.2 ohms. Measurements made are given in Table I., the columns being headed *f*, *R*

and L, which signify respectively frequency in cycles per second, resistance in ohms and inductance in milli-henrys.

TABLE I.

f	No. 1.		No. 2.	
	R	L	R	L
0	531.6		132.2	
180	550	94.3	155	95.0
274	575	83.3	155	87.0
415	605	75.2	180	84.0
674	650	63.0	205	74.5
745	665	62.0	220	74.5
748	675	64.5	230	75.2
950	665	54.5	230	67.0
954	680	55.0	245	68.0

TABLE II.

	No. 1.			No. 2.		
f	R	L	Z	R	L	Z
0	531.6		531.6	132.2		132.2
50	534	105.3	535.0	137	103.8	140.8
100	539	100.4	542.7	140	99.4	153.3
150	545	95.6	552.4	144	96.0	170.1
200	553	91.2	564.7	150	93.0	190.1
250	562	87.1	578.4	156	90.4	210.9
300	573	83.3	594.2	163	88.0	232.6
350	586	79.7	611.6	170	85.8	254.0
400	598	76.5	628.3	178	84.0	276.1
450	610	73.6	644.5	185	82.3	297.3
500	621	71.0	659.8	193	80.7	318.7
550	632	68.8	675.2	202	79.0	339.6
600	643	66.8	690.5	209	77.4	358.9
650	653	64.8	704.6	215	75.9	377.2
700	660	62.9	715.6	221	74.4	395.4
750	667	61.2	726.6	226	73.0	411.8
800	671	59.5	734.6	231	71.6	427.6
850	673	58.0	740.8	234	70.2	441.9
900	675	56.5	746.8	237	68.8	455.6
950	675	55.2	751.0	240	67.5	469.0
1000	675	53.9	755.4	241	66.2	480.8

From this table the resistance and inductance curves of Figs. 1 and 2 were plotted, Figs. 1 and 2 applying to telephones nos. 1

and 2 respectively. From the curves the values of resistance and inductance at frequencies up to 1,000 cycles per second by steps of 50 cycles were taken, and from the values the impedance Z was calculated in ohms. The results are given in Table II. and the impedance curves plotted in Figs. 1 and 2.

It will be noticed that the resistance and inductance tend toward a limiting value, while the impedance of course will increase indefinitely with the frequency.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

NOTE ON SPHERICAL ABERRATION.[1]

BY W. S. FRANKLIN.

THERE is much confusion at present in the terminology which relates to spherical aberration, and the publication of the interesting photograph, Fig. 1, gives an opportunity for calling attention thereto.

It would be seem to be desirable to use the general term spherical aberration for all those imperfections of a lens which lead to the production of non-spherical wave fronts. A very narrow pencil of rays passing through a lens parallel to the axis of the lens is not subject to spherical aberration because in the first place the transmitted waves are symmetrical

Fig. 1.

about the axis (equal curvature in every direction), and in the second place the transmitted waves are so small that they cannot be distinguished from sectors of a spherical surface. A broad beam of rays, however, is

[1] Abstract of a paper presented at the New York meeting of the Physical Society, October 24, 1908.

subject to spherical aberration when it passes through a lens parallel to the axis of the lens. A narrow pencil of rays which passes obliquely through a lens becomes a well-defined astigmatic pencil, and a broad oblique pencil or beam of rays is very greatly confused by a simple lens.

There are, therefore, three kinds of spherical aberration, namely, (*a*) spherical aberration of a broad pencil of rays which emanates from a point in the axis of the lens, (*b*) spherical aberration of a narrow oblique pencil of rays, and (*c*) spherical aberration of a broad oblique pencil or beam of rays. The first is called *axial spherical aberration*, the second is called *astigmatism*, and the third is called *oblique spherical aberration*, or *coma*.

The character of axial spherical aberration is beautifully shown by the accompanying Fig. 1. A broad beam of parallel rays passes through a moderately short-focus plano-convex lens, as indicated by the sketch lines in the figure, the region behind the lens is filled with smoke, and a

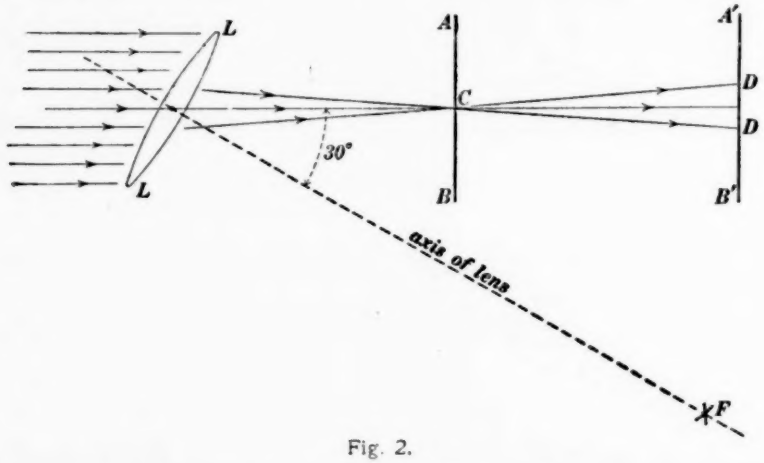

Fig. 2.

photograph of this illuminated smoke is taken. Ordinarily the caustic of a mirror or lens is thought of as a single surface, that is, a surface having a single sheet. As a matter of fact, however, a caustic surface is, in general, a surface of two sheets inasmuch as a wave front has generally two radii of curvature at each point. When a wave front is a surface of revolution one sheet of the caustic surface reduces to a line (the axis of revolution). Thus, in Fig. 1, the curved outline of the beam is one sheet of the caustic surface, and the brilliant line of light along the axis is the other "sheet" of the caustic surface. This brilliant line of light is formed by the focusing of the light at different distances from the lens by the different zones of the lens.

Fig. 2 shows, exactly one quarter size, a lens *LL* set obliquely to a

beam of parallel rays, and Figs. 3*a* and 3*b* show the spots of light which are produced upon photographic plates placed at *AB* and *A'B'*, respectively, in Fig. 2. The sharp distinction between astigmatism (that is, sspherical aberration of a narrow oblique pencil) and coma may b

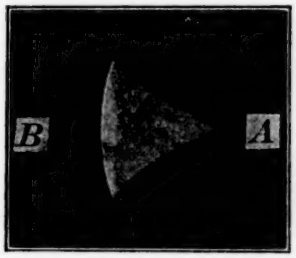

Fig. 3a.

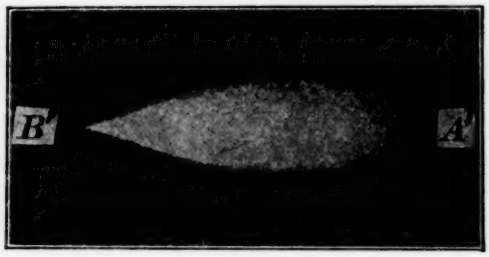

Fig. 3b.

hown in a very striking way by covering the lens *LL* in Fig. 2 by ae cardboard with a small hole at its center, when the spots of light shown in Figs. 3*a* and 3*b* reduce to the two sharply-defined lines *CC* and *DD* in Figs. 4*a* and 4*b*.

Fig. 4a.

Fig. 4b.

THE THEORY OF COUPLED CIRCUITS.[1]

BY LOUIS COHEN.

WITHIN the last few years several eminent physicists have made valuable contributions to the discussion of the theory of coupled circuits, but to my knowledge none of them succeeded in giving the complete solution of the problem. They had to resort to some method of approximation in one form or another.

The main difficulty involved in the solution of this problem is that it is necessary to obtain the four roots of a biquadratic equation. Theoretically, it is of course possible to do so, but practically the task is rather difficult, particularly so in this case where it happens that the various coefficients are complicated functions of the constants of the circuits.

I have succeeded in developing a method which enables me to avoid

[1] Abstract of a paper presented at the Baltimore meeting of the Physical Society, December 28–31, 1908.

this difficulty entirely. In place of the biquadratic, I can reduce the problem to two simple quadratic equations. Furthermore, all previous investigators limited themselves to the discussion of the case of electromagnetic coupling, and the case of direct coupling has been ignored entirely. My method, however, enables me to obtain the complete solution of both cases.

The work involved in the development of the theory is necessarily complicated, and it will not be possible to give in an abstract even an outline of the method adopted, so I shall merely limit myself in giving the final results obtained.

If we designate by V_1 and V_2 the potentials at any instant in the primary and secondary circuits respectively, then we shall have for the case of electromagnetic coupled circuits

$$V_1 = \{H_1 e^{-\alpha_1 t} - H_3 e^{-\alpha_2 t}\} \cos \lambda_1 t + \{H_2 e^{-\alpha_1 t} - H_4 e^{-\alpha_2 t}\} \cos \lambda_2 t,$$
$$V_2 = H_5 \{e^{-\alpha_1 t} - e^{-\alpha_2 t}\} \cos \lambda_2 t + H_6 \{e^{-\alpha_1 t} - e^{-\alpha_2 t}\} \cos \lambda_2 t.$$

The constants H_1 to H_6 are somewhat complicated functions of the constants of the circuits and their values will be given in the complete paper which will soon be published. The values of the damping factors are as follows:

$$\alpha = \frac{L_2R_1 + L_1R_2 - \sqrt{(L_2R_1 - L_1R_2)^2 + 4R_1R_2M^2}}{4(L_1L_2 - M^2)},$$

$$\beta = \frac{L_2R_1 + L_1R_2 + \sqrt{(L_2R_1 - L_1R_2)^2 + 4R_1R_2M^2}}{4(L_1L_2 - M^2)}.$$

λ_1 and λ_2 are the frequency constants and their values are given by the following equations:

$$\lambda_1 = \sqrt{\frac{2(a_1a_2 - d_1d_2)a^2 + (a_2b_1 + a_1b_2)a + (a_1 + a_2) + \sqrt{d_1d_2\{(b_1 + b_2)a - 2\}^2 + 2\{(a_2b_1 - a_1b_2)^2 + d_1d_2(b_1 - b_2)^2\}a^2}}{2(a_1a_2 - d_1d_2)}}$$

$$\lambda_2 = \sqrt{\frac{2(a_1a_2 - d_1d_2)a^2 + (a_2b_1 + a_1b_2)a + (a_1 + a_2) - \sqrt{d_1d_2\{(b_1 + b_2)a - 2\}^2 + 2\{(a_2b_1 - a_1b_2)^2 + d_1d_2(b_1 - b_2)^2\}a^2}}{2(a_1a_2 - d_1d_2)}}$$

The various letters used have the following significance:

$$a_1 = L_1C_1, \quad b_1 = R_1C_1, \quad d_1 = MC_2$$
$$a_2 = L_2C_2, \quad b_2 = R_2C_2, \quad d_2 = MC_1$$

where L_1, R_1, C_1 and L_2, R_2, C_2 are the inductance resistance and capacity of the primary and secondary respectively, and M is the mutual inductance.

For the case of direct coupled circuits, we have:

$$V_1 = \{D_1 \cos \lambda_1 t + D_2 \cos \lambda_2 t\} e^{-at}$$

$$V_2 = \{F_1 \cos \lambda_1 t + F_2 \cos \lambda_2 t\} e^{-at}$$

where

$$\lambda_1 = \sqrt{\frac{L_1 C_1 \frac{L_2}{L_1 + L_2} a^2 - R_2 C_2 a + 2 + \sqrt{\frac{L_1}{L_1 + L_2}(R_2 C_2 a - 2)^2 + \frac{L_2}{L_1 + L_2} R_2^2 C_2^2 a^2}}{2 L_1 C_1 \frac{L_2}{L_1 + L_2}}}$$

$$\lambda_2 = \sqrt{\frac{L_1 C_1 \frac{L_2}{L_1 + L_2} a^2 - R_2 C_2 a + 2 - \sqrt{\frac{L_1}{L_1 + L_2}(R_2 C_2 a - 2)^2 + \frac{L_2}{L_1 + L_2} R_2^2 C_2^2 a^2}}{2 L_1 C_1 \frac{L_2}{L_1 + L_2}}}$$

$$a = \frac{R_2}{2 L_2}$$

The constants of course have the same meaning as given above.

The expressions for the currents in the circuits can be derived from the potentials, and they are given in the complete paper.

WASHINGTON, D. C.

ENTLADUNGSSTRAHLEN.[1]

BY ELIZABETH R. LAIRD.

IN 1895 Wiedemann and Schmidt, and in 1897 Hoffman published work describing a particular effect in the neighborhood of the spark at atmospheric pressure which they ascribed to a kind of radiation named by Wiedemann "Entladungsstrahlen." The effect was that certain substances were made thermoluminescent by this means under conditions in which they could not be made so by exposure to light. Later J. J. Thomson showed that this radiation would ionize the gas through which it passed.

Some time ago the writer while at the Cavendish Laboratory confirmed one of Hoffman's results showing that at a pressure of a millimeter or two radiation comes from a spark capable of traversing two layers of paper and affecting a photographic plate and that a quartz plate or metal objects are opaque to it. At the same time attempts were made by the electrical

[1] Abstract of a paper presented at the Baltimore meeting of the Physical Society, December 28–31, 1908.

method to see if any of the radiation would be transmitted through thin aluminum, but with negative results.

Later an electrical effect was sought through thin aluminum at somewhat reduced pressures, with negative results also except when the connections were such hat the aluminum was covered with a faint glow on the side opposite the ionization chamber.

The present work includes the repetition of a number of Hoffmann's experiments and was undertaken since the question has been raised as to whether these rays differ from ordinary light rays or from ions. The thermoluminescent method of detection was chosen, and a solid salt solution of calcium sulphate + 2 per cent. manganese sulphate was used for the purpose. According to Hoffman when this is heated it loses its power of becoming thermoluminescent when exposed to light, but regains it when exposed to the spark. This, after some trials with different samples of salt, was confirmed, and a piece of quartz used as test during the course of the experiments always acted as an opaque object. The arrangements for observing the thermoluminescence were similar to those used by Hoffmann, a small radioscope was used to test the sensitiveness of the eyes before observations. In the greater number of experiments the salt was deposited on mica instead of on copper, as used by Hoffmann, to avoid chance electrical disturbances due to the metal.

When a small Wimshurst machine was used about double the capacity of the small Leyden jars forming a part of it had to be used to obtain a marked effect. If pointed electrodes were used instead of rounded ones the salt had to be placed nearer to obtain the same effect, and in this case no thermoluminescence was observed unless some capacity was used. This agrees in general with Hoffmann's observations and would show that the radiation from some forms of discharge is more easily absorbed or less in quantity, and also that the effect is not due to slow moving ions.

To test this further an air current was passed over the surface of the salt at right angles to and below the spark of an induction coil. When the salt was heated the shadow of the tube from which the air current came could be plainly seen, but no diminution in intensity could be observed in its path, although the speed at the outlet computed from the amount of air used was over 200 cm./sec.

A magnetic deflection was sought by Hoffmann and not found. A different method used here gave the same result. A number of experiments were made. In one a magnetic field estimated at 8,000 C.G.S. units was used. The spark from a Holtz-machine was the source, and was at right angles to and above the poles of the electromagnet. Below the spark and just above the poles was a slit made in a piece of mica, below the poles was the salt. A strip on the salt was exposed with the magnetic field on. The salt was then moved parallel to the magnetic

field and a similar strip exposed with the current off. The salt was then heated and the two bands of light compared. One edge was especially sharp, and no displacement of one relative to the other was observed, also the distribution of light in the two corresponded closely. The radiation had to traverse this field a distance of over 2 cm. Any ions of cathode ray magnitude would have been deflected, or if of atomic magnitude unless moving with velocities over 10^8 cm./sec.

The absorption of the radiation in air was observed especially with the spark of the induction coil as source. At a distance of 1.5 cm. the thermoluminescence was bright, at 4 cm. for the same time of exposure none at all was observed, and with three times the exposure, at a distance of 2.5 cm., the brightness was not over half the original, although an inverse square law would make these about equal. A current of impure oxygen from a gas cylinder passed over the salt while it was being exposed to the spark did not diminish the brightness especially. The effect of carbon dioxide was studied by placing the salt in a glass dish, the cover of which contained a slit and which was partly filled with solid carbon dioxide. When the distance of the salt below the cover was about 4 cm. and from the spark of the Holtz machine about 6 cm., a diminution in brightness was observed, so that increasing the time of exposure one half did not give quite as bright thermoluminescence as obtained with air at the same distance and for the same time of exposure. These experiments with carbon dioxide were repeated on three different days, in all seven times, and with the same general result which differs greatly from that obtained by Hoffmann.

When the salt was deposited on copper, it was noted that, when the induction coil was used, the greater thermoluminescence was on the side of the anode. This was traced to a projecting point on this side which slanted down somewhat towards the salt and was covered with a glow of light. A similar effect was obtained by curving the German silver wire forming the electrode downwards. If the current in the coil were reversed no special effect was noted under the projecting point, it was also absent when the salt was deposited on mica. This seemed to indicate that it might be due to the metal acting partly as cathode. It was found also that if a hissing discharge from the Wimshurst machine passed directly to the plate the greater thermoluminescence was on the side towards the positive electrode.

Thermoluminescent effects similar to those obtained in the above experiments followed if the salt were placed under a bend in a wire inserted in the secondary of the induction coil on either the positive or negative side of the spark gap, this effect was likewise cut off by quartz. No appreciable effect was obtained from a thin strip of aluminum inserted in a circuit consisting of a short spark gap and Leyden jar charged from the induction coil, but the power used was small.

These experiments tend to confirm the existence of something coming from the spark other than light or slow moving ions, which is not readily deflected, if deflected at all, in a magnetic field, which is absorbed by air and to a somewhat greater extent by carbon dioxide, and which may be called Entladungsstrahlen.

MAGNETIC DOUBLE REFRACTION NORMAL TO THE FIELD IN LIQUIDS.[1]

BY C. A. SKINNER.

COTTON and Mouton[2] discovered recently that nitrobenzol when placed in a magnetic field becomes double refracting in a direction normal to the field, and that this property follows Kerr's law for double refraction in an electric field. They found also that the dispersion in the two fields is the same within an accuracy of measurement of two per cent. in the violet and ten per cent. in the red region of the spectrum.

Possessing in the Brace half shade elliptic polarizer a very sensitive means of measuring double refraction of this kind; and the results o McComb,[3] who has been making an extensive study of electric double refraction of liquids in this laboratory, I have been led to investigate electric double refracting liquids in general for the presence of corresponding magnetic double refraction.

Of fourteen liquids thus far investigated, eight show a measurable relative retardation of the vibration perpendicular to the field (as compared with that parallel to it) in both electric and magnetic fields; two show a relative retardation of the parallel component in both; one, a relative retardation of the perpendicular component in the electric field, and of the parallel in the magnetic; one a measurable effect in the electric, but nothing observable in the magnetic field; and two show the effect in the magnetic, but nothing observable in the electric. Of these, nine have been compared for dispersion, showing without exception that this is the same in the two fields.

Kerr's law for electric double refraction may be stated thus:

$$\delta_e = B_e E^2 l$$

in which δ_e = number of waves of the perpendicular vibration minus number of waves of the parallel vibration in a length of l centimeters of the liquid normal to the electric field of intensity E electrostatic units. B_e = the value which δ_e takes for unit length of path in unit field.

[1] Abstract of a paper presented at the Baltimore meeting of the Physical Society, December 28–31, 1908.

[2] Compt. Rend., July, 1908.

[3] See abstract of paper in PHYS. REV., Sept., 1908.

The corresponding law for magnetic double refraction is

$$\delta_m = B_m H^2 l$$

in which H is the intensity of the magnetic field in C.G.S. units.

The following table is a brief summary of the results obtained with a tube of liquid 6 cm. long in a magnetic field of about 14,000 C.G.S. units. The values of B_e were furnished by Mr. McComb.

	B_m ($\lambda = 500$)	B_m/B_e (for all values of λ)
Nitro benzol	34×10^{-13}	1.06×10^{-7}
Nitro toluol	21	1.61
Chlor benzol	11.4	8.3
Brom benzol	10.5	8.8
Benzol	9.0	176
Di ethyl aniline	6.8	4.9
Di methyl aniline	9.7	8.1
α-naphthalene bromide	33	30
Carbon bisulphide	-5.3	-12.8

It appears rather remarkable that although carbon bisulphide shows a different component to be relatively retarded in the magnetic field to that in the electric yet the ratio B_m/B_e is, within the limits of experimental accuracy, the same for all wave-lengths ranging from 440 to 660×10^{-7} cm.

The question as to how accurately the double refraction is proportional to the square of the strength of the magnetic field has not as yet been thoroughly investigated.

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UNIVERSITY OF NEBRASKA.

NEW BOOKS.

Experimental Elasticity. By G. F. C. SEARLE. Cambridge Physical Series, 187. Pp. xvi. G. P. Putnam & Sons, 1908.

There is perhaps no topic in mechanics more difficult for the average student than elasticity, and yet none of more vital importance in all practical applications. As a rule, authors either make the treatment almost meaningless by the assumption of all formulæ without any notion of their physical basis, or else plunge the student into a maze of mathematical symbols both confusing and devoid of physical interest. It is consequently refreshing to have a book at once physical in spirit and yet using to advantage such mathematical tools as the student should be expected to possess at the stage represented by this work.

The first portion of the book contains a discussion of elementary principles, of elastic constants and their relations, including the relation between adiabatic and isothermal expansions. This is followed by the "solution of some simple elastic problems," which are quite suggestive of methods useful in more complex cases. Then follows a laboratory course of fourteen experiments very clearly stated and with perhaps an overabundance of suggestion.

Several related topics are treated in the "notes" which constitute a large part of the book. Note X, on "laboratory work," may be read with profit by any student or teacher.

J. S. SHEARER.

Refrigeration. An Elementary Text-book. By J. W. ANDERSON. Pp. ix + 242. Longmans, Green & Co., 1908.

The rapid development of practical refrigeration has created a demand for books dealing in a general way with this topic. This volume is a rather popular presentation of the elements of refrigeration theory and practice. The first fifty pages contain a review of elementary heat such as is found in most text-books. Then follows a discussion of the construction and installation of refrigerating machinery and of the special applications now common. Details relate almost entirely to English practice which will not increase the value to American readers.

The use of both English and metric units is unfortunate in a book of this kind as it is often confusing and serves no useful purpose. The problems which are solved in the text will be of considerable assistance to the non-technical reader.

J. S. SHEARER.

Electrical Engineer's Pocket-Book. Fifth Edition. By HORATIO A. FOSTER. Pp. xxxvi + 1599. New York, D. Van Nostrand Company, 1908.

This new edition, containing 600 pages more than previous editions, is practically a new book; in all parts the revision has been complete. The amount of information given in condensed form is simply enormous, and certainly the compiler deserves the thanks of all who use the book for making the information so readily available.

During the last year we have been given two excellent hand-books; as in the case of two telephone systems, each one no doubt is better on account of the other. In the case of these hand-books, each serves to supplement and to check the other. Any worker in electricity needs one handy; and the other somewhere accessible.

It is open to question whether the term "practical unit" should be applied to any unit which does not belong to the "practical system." The *Gauss* and *Maxwell*, for example, are names applied to certain C.G.S. units. These are not units of the practical system; neither is the kilowatt. The term "practical," when applied to these units, is used in a popular rather than a technical sense. It seems unfortunate to longer preserve the term *static* transformer, the adjective being unnecessary and even misleading. F. B.

Illustrated Technical Dictionary in Six Languages: English, German, Russian, Italian, Spanish. Edited by K. DEINHARDT and A. SCHLOMANN, Vol. II.: Electrical Engineering. Compiled by CHAS. KINZBRUNNER. Pp. xii + 2100. Munich and Berlin, R. Oldenbourg; New York, McGraw Publishing Co., 1908.

The scheme of this dictionary and its execution are both excellent. A topical rather than alphabetical arrangement is employed, bringing together all words pertaining to one subject; a finding index is appended. The illustrations, of which there are about 4,000, add materially to the value of the book. The work has been prepared by a permanent staff, over thirty in number, assisted by several hundred co-operators.

Electro-Metallurgy. By JOHN B. C. KERSHAW. Pp. xv + 303. New York, D. Van Nostrand Company, 1908.

With no attempt at discussing theory, the author gives a clear account of the manufacture of aluminum, bullion and gold, calcium carbide and acetylene gas, carborundum, copper ferro-alloys, glass and quartz glass, graphite, iron and steel, lead, miscellaneous products, nickel, sodium, tin and zinc.

The processes are adequately described in a manner that can be understood by those whose acquaintance with either chemical or electrical

science may be but slight. The author has collected much valuable information in this rapidly developing field.

The Theory, Design and Construction of Induction Coils. By H. ARMAGNAT. Translated and edited by O. A. KENYON. Pp. v + 216. New York, McGraw Publishing Company, 1908.

With the increased use of the induction coil in wireless telegraphy, electrotherapeutics, gas-engine ignition, etc., there is an increased demand for exact knowledge concerning it; this demand is well met in the present book. A good description is given of various forms of interrupters, and a full discussion of the theory of mechanical and electrolytic interrupters. The bibliography — to which the translator has added — is particularly valuable, containing 104 references, many of which are briefly abstracted. The translator and the publishers have succeeded in producing an attractive edition of this little book.

Electric Lighting and Power Distribution. By W. P. MAYCOCK. Vol. I. Seventh Edition. Pp. xix + 599. London, Whittaker & Co., 1908.

This is an elementary book, intended particularly for English students preparing for the examinations of the City and Guilds of London Institute. It is clearly written and deals in a satisfactory manner with the elementary laws of electricity and magnetism, and with measuring instruments, but — save for the discussion of the dynamo — scarcely touches the subject of lighting and power distribution, nor the subject of alternating currents. Presumably these topics are reserved for Vol. II. In this edition, the book has been much enlarged.

The Principles of Alternating Currents. By EDGAR T. LARNER. Pp. viii + 136. New York, D. Van Nostrand Company, 1908. (Received.)

Die elektrischen Eigenschaften und die Bedeutung des Selens für die Elektrotechnik. By Dr. CHR. RIES. Pp. i + 86. Berlin, Nikolassee, Administration der Fachzeitschrift, der Mechaniker, 1908. (Received.)

Histoire du Developpement de La Chimie Depuis Lavoisier Jusqu'a Nos Jours. By A. LADENBURG. Traduit sur la 4^{e} edition allemande by A. CORVISKY. Librairie Scientifique, A. Hermann & Fils. 1909. (Received.)